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# LAND USE – ENERGY SIMULATION MODEL

## A COMPUTER-BASED MODEL FOR EXPLORING LAND USE AND ENERGY RELATIONSHIPS

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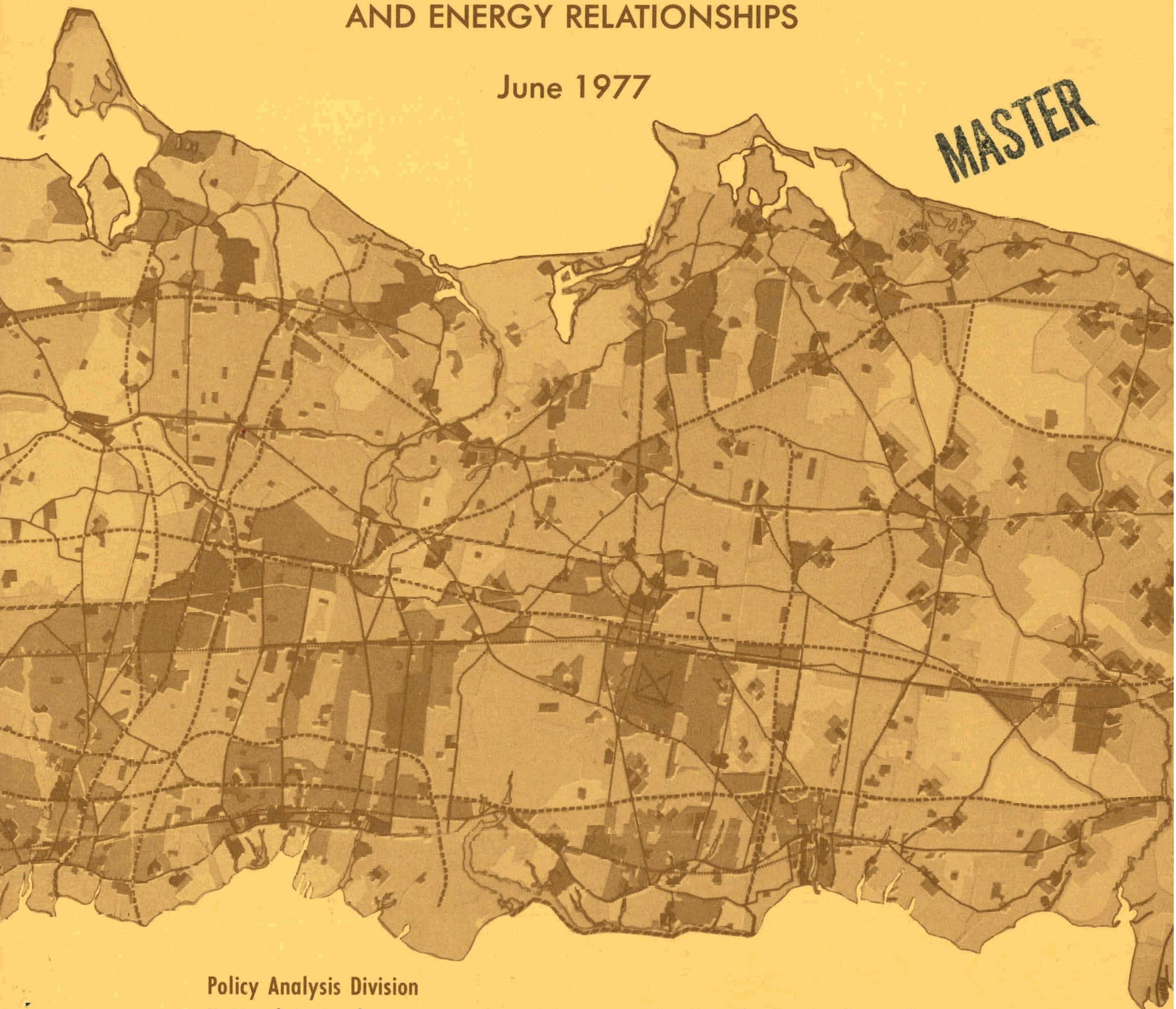

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# LAND USE - ENERGY SIMULATION MODEL

## A COMPUTER-BASED MODEL FOR EXPLORING LAND USE AND ENERGY RELATIONSHIPS

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## Abstract

There is no doubt that major conservation of future regional energy expenditures can be achieved through the propitious allocation and configuring of land use activities. The task of searching for and selecting strategies and measures which will bring about energy conservation vis-a-vis land use becomes that of understanding and defining relationships between sets of possible land use activities in a given region and the resultant energy end use demand. The outcome of the search is the determination of the relative impact of the strategies and measures upon both the regional and national energy system.

The Land Use-Energy Simulation Model with integrated capability for generating energy demand is an extension of the classic Lowry model. Such a model framework captures two essential features of the land use-energy utilization interaction; first, the spatial location of land use activity is implicit, and second, transportation energy demand is determined as an integral part of the spatial configuration. The model is divided both conceptually and computationally into three parts; the land use model, a submodel for transportation which provides the work and shop trip distributions for spatial allocation of activities within the land use submodel, and an energy submodel which determines the energy demand from the land use configuration.

Two specific types of applications of the computer model are described. The model was utilized to assess the energy demand of the Long Island region in New York. Second, the model was applied to study the generic relationships between energy utilization and urban form. In the first instance, energy savings of 50% are associated with transportation requirements for alternative land use patterns, and total energy savings in incremental growth of up to 20% can be attained through introduction of accepted land use plans prepared by regional planning agencies. In the more general sense, the modeling results are suggestive of lower energy consumption associated with less centralized cities, but further exploration with the model is required before a definitive statement can be made concerning the magnitude and direction of the complex interactions underlying land use patterns.

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## I. INTRODUCTION

The uses to which land is put and the factors which influence these uses affect almost every facet of a community's or a region's livability. The land use planning process has recognized many of these factors and attempted to include them in preparing designs for future land use development or in projecting future land uses. Within the past few years, it has become clear that for many areas of the country both the manner in which energy is consumed within the region and the forms taken to accomodate that demand will have an important bearing on these designs and projections. In part this realization is the result of federal and state policies which are aimed at reducing total energy expenditures and in shifting the use of fuels to those which are in more plentiful supply. It also stems from the knowledge that imbalances in regional energy supply and demand can result in wide-ranging economic, social, and environmental dislocations.

Examples of the interplay between land use, regional development, and energy utilization are numerous and diverse:

> The development of urban interstate highway networks has quickened and extended the spread of residential and industrial development to outlying areas. These, in turn have lead to greater per capita energy consumption and higher demands for oil and electricity.
>
> The construction of electric generation stations, oil refineries, and storage facilities often interferes with other land uses in nearby and adjacent areas and can lead to increased environmental risks to area inhabitants.
>
> The location of energy-intensive industrial development within the country is increasingly affected by prevailing prices and availability of fuels. Such shifts not only can have serious impacts on regional economies and employment, but can directly effect the mix of resulting land uses throughout the country.

From the point of view of analyzing both policies which seek to modify energy consumption through changes in land uses and regional land use impacts of energy supply system constraints, what is needed is a better understanding of the inter-relationships between regional land use and the energy supply-distribution-demand system. This requires a framework for viewing these relationships within the context of an overall set of regional development goals and preferences, the available technologies which can be utilized to supply, convert, and consume energy, and the stated energy goals and priorities of the nation. It also requires a methodology for characterizing land uses so that their associated energy and fuel demands can be quantified in a manner which takes into account local conditions and available data sources. Finally, it requires a land use-energy simulation model which is able to allocate regional land use activities based on region-specific input and estimate resulting energy demands.

## A. Aim of this Report

The Land Use-Energy Utilization Project represents an initial effort to provide such a framework, methodology, and model. In this study, which is supported by the Federal Energy Administration, we have focussed special attention on the needs of both federal agencies and local planning groups. For the first group, the results are directed toward increasing the understanding of the way in which regional land use trends throughout the country will impact on federal policies and goals, particularly in the area of energy conservation. For the second audience, the study is aimed toward delivering a decision tool and information base which will allow them to explore both the energy implications of alternative land use development patterns and the impacts of energy supply and distribution constraints on land use development.

An interim report issued in October 1975 describes the conceptual framework, a methodology for calculating land use-energy intensity coefficients, and a preliminary version of the land use-energy model.[1] A second report has been issued that offers local planners a workbook for calculating current and projected energy demands in their areas.[2] This workbook provides a basic set of information on energy intensity factors in the major land use sectors, describes procedures for modifying these factors to take into account local conditions, and presents illustrative case examples of the use of the methodology.

This report focuses on the land use-energy simulation model. It presents a detailed description of the model, the procedures used to calibrate it, and several examples of its application.

The basis of the model is similar to that of the more common transportation and land-use planning models in use,[4] and the land use-energy simulation model is directed to that part of the planning professions which utilizes computer models as one of its tools in assessing the impacts of land use development and regional growth.

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## II. MODEL DESCRIPTION

### A. Systems Framework in Which the Model is Used

To understand the specific approach we have taken in formulating the land use-energy model, it is necessary to review both the overall systems framework of which it constitutes a part and the intended uses of the model.

Figure 1 shows in diagramatic form the conceptual framework we have utilized for analysis of the relationships between land use development goals, preferences, and constraints and their regional and national energy implications. This diagram identifies the basic elements which enter the land use-energy linkages and those points in the system where intervening strategies and measures are likely to bring about changes in existing energy-use practices and land use development trends. As seen in the figure, our approach acknowledges that the primary driving forces which define the mix, levels, and spatial arrangement of land use activities in a region are most often found to be exogenous to energy considerations. They result from a variety of external economic, social, and political conditions, many of which are set by factors beyond the control of the region. Some of these, however, are identifiable targets or goals for regional development, such as population, employment, and industrial rates.

Regional preferences with respect to industrial development, mix of activities, zoning, open space, etc. also enter into regional development, as do certain physical characteristics of the terrain and existing land uses.

A knowledge of these regional development parameters and descriptors does not, in general, yield a set of land use activities which is defined with sufficient precision to assess the projected energy demand. The purpose of the land use-energy simulation model is to provide this allocation for each of the major land use sectors - residential, commercial, industrial, and transportation and to partition the end-use sectors among the available space in the region in a manner that is consistent with regional development goals, and constraints. Once this detailed set of land use activities is obtained from the model, one can evaluate the projected energy demand for the region utilizing the energy intensity coefficients associated with each sub-sector of land use activity.

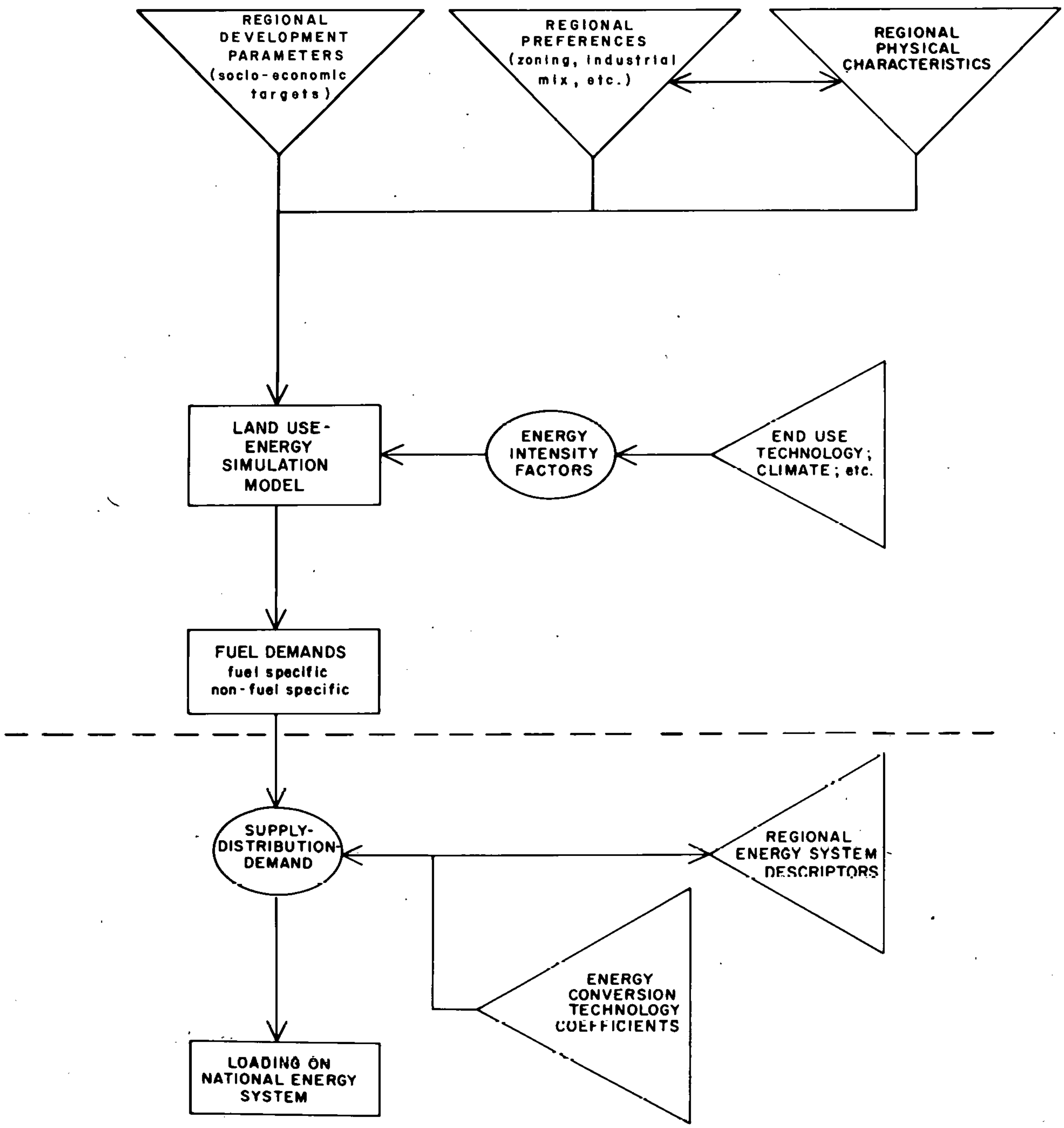


Figure 1. Framework for search and selection of energy-conserving land use patterns.

The specification of energy intensity must both relate to conventional land use categories used by planners and be consistent with the varying manner in which energy is consumed by these activities. The output of the land use-energy simulation is then a set of energy demands associated with residential, commercial, industrial, and transportation activities of the projected land use configuration.

The designation of fuel specificity for appropriate end use sectors and of the mix of fuels needed to supply these regional energy demands is a product of three interacting factors. First, end use technologies are utilized to provide the services for which energy is being consumed. For example, if we specify the percentage of personal travel demands in the region that will result from the use of conventionally-powered automobiles, and the energy efficiency of these vehicles, we can project the amount of gasoline that will be required to meet the regional energy demands specified by the land use-energy model outputs. Second is the regional energy supply-distribution system, which may act to limit the total amounts of fuels available to the region. Gasoline deliveries to the region, for example, may be limited by import facilities, pipeline capacities, etc. Since the production, processing, and distribution of energy are themselves land use activities, and have their associated environmental effects, regional preferences exert an influence on the choice of sites for their location and the energy conversion technologies used (e.g., nuclear vs. coal-fired electric generating stations). The third factor is the national energy system. Through policies affecting energy prices, the availability of specific fuel types, and choice of energy supply technologies, this system operates to influence both the regional supply-distribution system end-use technologies, and land uses.

To analyze these regional and national energy system impacts on fuel demands and to insure that an internally consistent set of data and information is used to describe these systems, we utilize the models and data formats which have been developed at Brookhaven National Laboratory for national and regional assessments.

Using the Systems Framework

The land use-energy simulation model forms an essential component in developing an understanding of the land use-energy system interactions. Since it was designed as a planning tool, the policy variables in the model reflect regional development parameters such as location of new industry, residential zoning, and certain characteristics of transportation sector which are of direct interest to the planner. It also includes regional development goals such as desired levels of population, employment, housing mix, etc. At the same time, the model contains an explicit identification of the basic descriptors of each land use activity which will account for the magnitude and form of its associated energy demands.

Characterizing and quantifying the special relationships between the level, mix, and spatial arrangement of land uses and their energy demands requires that we formulate a system of differentiating land use activities which (1) is familiar to land use planners, (2) is able to reflect the varying levels of economic development in the region, (3) displays their relative contributions to total regional energy demands (or to the demands on particular fuel types), (4) distinguishes between activities which are more apt to respond to available energy supplies, and (5) allows the effectiveness of energy conserving technical process to be included. It also requires that we seek varying levels of aggregation of land use activities in the individual sectors which (1) are compatible with the limited nature of available data, (2) utilize available submodels to estimate the effects of regional differences in climate, energy uses practices, and construction types on energy demand, and (3) allow where necessary the specification of individual fuels needed to satisfy the services for which the energy is employed, and (4) yield values for the energy intensity factors which are relatively constant throughout the region.

In the model each major sector of land use activities is subdivided into a number of categories and their energy (and fuel specific) demands estimated on the basis of surveys of existing information and data sources. The energy demands per unit activity, which are the land use energy intensity factors, thus represent average values for a composite set of end-use services within the land use activity category for which energy is being consumed. The energy intensity factor for the single-family dwelling category, for example, contains information specific to the region on average energy consumption for space heat, air conditioning, and minor and major appliances. To cast these land use-energy demands in terms familiar to planners, we use different units in different land use sectors -- dwelling unit in the residential sector, square footage in the commercial sector, industrial sales or number of employees in the industrial sector, and vehicle miles in the transportation sector. The spatial element in specifying the final land use pattern is captured in the transportation sector of the model which takes into account both the existing transportation network and knowledge of national and regional travel patterns.

The application of the conceptual approach outlined in Figure 1 usually consists of three basic steps:

1) A "business-as-usual case" is prepared in which the input parameters (zoning, industrial development, etc.) to the land use-energy simulation model represent continuation of present trends. The resulting energy and fuel demands are then compared with the outputs of the regional energy supply system. Loadings on the national energy system are estimated.

2) Alterations are then introduced into the inputs of the land use-energy simulation model which result in a changed land use pattern and set of energy end-use demands which are differentiated between fuel specific and non-fuel specific demands.

3) The Brookhaven supply-demand models can then be used to determine minimum cost fuel allocation to meet these demands. Included in these models are any constraints imposed by regional preferences, the energy production and conversion technologies utilized, and national supply availabilities.

B. Existing Models

Our approach to the design of a land use-energy utilization model reflects a variety of concerns. These include the policy variables and parameters which should be accessible in the model, its ability to capture the complexity of land use and energy demand patterns without becoming too cumbersome, and the ease with which the model structure might be adapted to local conditions in different regions. Other land use and energy models have had to deal with similar questions. Therefore, we have reviewed some of the more widely known models in the fields of land use and of energy systems. There is, of course, no a priori reason to anticipate compatability between any of the existing models of land use and those of energy systems, since successful models which have been developed in each of these areas have arisen from essentially disjoint sets of policy interests. Our review was intended rather to shed light on those model structures and conceptual approaches which have been successfully implemented. In this respect, a number of existing models have provided useful input in our conceptualization of land use-energy utilization relationships and the modeling approaches.

Land Use Models. Modern regional land-use models are outgrowths of work initiated in the early fifties that was intended to assist planners in the design of transportation systems. Most early models were based upon a factoring-up of existing land-use patterns, and few employed recursive systems of any kind. The models were not designed with the internal self-adjustment over time necessary to reflect dynamic change. It was not until approximately 1960 that dynamic land use models began to be developed.

Perhaps the most significant of the early land use modelling studies was the Detroit Area Transportation Study[5] (1955), which is primarily noted for its innovations in the quantification of intersector "activity" relationships. Three particularly well known works that appeared in the mid-1960's changed the course of land-use modelling significantly: Britton Harris' work on linear programming and land-use for the Penn-Jersey Transportation Study;[6] Kenneth Schlager's suggestions for a land use design model constructed with a linear programming format;[7] and Ira S. Lowry's Model of Metropolis for the RAND Corporation,[8] an approach which spatially allocates commercial and residential employment within a region from exogenously determined basic employment data. This model was developed as a part of a system designed to generate land-use alternatives for decision making purposes in the Pittsburgh Comprehensive Renewal Program.[9]

The Lowry model is significant not only for its innovation theoretical features, but for its operational applicability. Several important land use development studies in the late 1960's and early 1970's embodied the basic Lowry model characteristics. The CONSAD Corporation application in Pittsburgh (TOMM)[10] expanded the model by disaggregating the household sector by various characteristics. The Bay Area Simulation Study (BASS 1) of 1965,[11] the Projective Land Use Model (PLUM) of 1968 incorporated in the Bay Area Transportation Study Commission (BASTC),[12] and the Cornell Land-Use Game (CLUG) of 1966[13] are all Lowry-based. It should be noted that the Lowry model has had the additional advantage of having been empirically tested. The model has been applied extensively on a subregional basis in England,[14] and perhaps the most intensive application has occurred with the Ljubljana Model (1970) of American-Yugoslav Project[15] which demonstrates land-use model applications in urban and regional planning.

Energy Models. The class of energy models is extremely large, and they span a much longer period in history than the land use models. Much of the early thrust of energy models focused upon the economics of supply and demand in specific fuels. Such models were developed by and for public and private producers. Examples are electric utility forecasting models[16] which attempted to assess strategies for capacity expansion, and models of oil company optimal allocation of crude and refined products between sources, refineries, and final demands at specified future dates.[17]

More recently, modelling efforts have been directed toward national policy issues. There are several conceptual tracks followed by such models, and each offers a different perspective on the energy system. Generalized systems modelling, for example, has been applied to the issue of interfuel substitutions. Simulation of flows of energy resources to end use demands is based upon formulations of energy system costs, investment decisions, and constraints upon supplies of resources. The model creates a set of energy prices, quantities available, and utilization of energy resources over time. Network and linear programming formulations of the energy system have been used extensively in technology assessment.[19] All steps in the energy chain, including extraction, refining, conversion, storage, transmission, distribution, and end use device are represented. Each such process is described by conversion efficiency, capital and operating cost, and pollutant emissions. The model is then used to assess energy-economic-environmental impacts of projected new technologies. Input-output analysis of energy in the national economy also proves valuable.[20,21] Here, the dollar transaction matrix, at differing levels of disaggregation, is augmented with energy consumption per unit of output. This permits study of the direct and indirect energy costs of consumer products, time trends of these energy coefficients, and even shifts in the employment-energy intensity of industry over time.[22] Analysis of fuel demand in response to a detailed, comprehensive forecast of the economy has also been prepared.[23] Modified macro-economic models have been used in the same context.[24] There is also considerable interest in coupling energy system models to national economic models, to draw upon the best features of each.[25] Interfuel substitutions in the network representation of the energy system imply changes in technological coefficients in the input-output matrix. The Brookhaven Energy System Optimization Model[26] is run in conjunction with the University of Illinois input-output model[27] to refine projected energy flows and assure compatibility between energy availability and national GNP.

The range of modeling efforts is far wider than might be imagined from this brief review but the description does convey some feeling for the potential breadth of energy modeling which has taken place.

C. Model Formulation

The Brookhaven-Stony Brook Land Use-Energy Simulation Model is an extension of an extension of the classic Lowry model.[28] We have modified the Lowry model in several important ways. The housing sector has been disaggregated into as many as five structural types. The housing, commercial, and industrial sectors are disaggregated into sub-sectors suitable for energy demand calculations by an energy submodel. The Lowry algorithm for the distribution of residential activity has been modified to enable consistent computation of work trip patterns.[29] Network algorithms are used to establish intertract travel times and distances. Such a model framework captures two essential features of the land use-energy utilization interaction:

1) the spatial location of land use activity is explicit, and
2) transportation energy demand is determined as an integral part of the spatial configuration.

The land use-energy simulation model itself is divided both conceptually and computationally into three parts: the land-use model shown by the bold lines in figure 2, a submodel for transportation which provides the work and shop trip distribution for spatial allocation of activities within the land-use submodel, and an energy submodel which determines energy demand resulting from the land use configuration.

Regional growth in the model is predicated upon an industrial employment base and the existing transportation infrastructure. Site-specific manufacturing and other industry dependent upon the interregional transportation network or the availability of local resources, such as water, is termed "basic" industry (all employment located outside the region is also considered "basic"). The region is divided into tracts and, for basic industry, the employment and acreage are specified for each tract. Using a trip distribution function derived from the transportation network, which measures preference for travel in the region, a residential population is spatially allocated consistent with industrial employment opportunities.[29] Retail and other commercial activity, such as offices and schools, measured by employment opportunities is also spatially distributed using the characteristics of the transportation network for residential-commercial travel. Zoning and measures of agglomeration are expressed as constraints upon location of activities in specified tracts. The sequence of regional development is portrayed through appropriate intervention into growth in industrial employment, zoning changes, housing mix, and modifications in the transportation network representation.

The model is adapted to the determination of energy demands in several importing respects. The residential sector is disaggregated into types of housing within

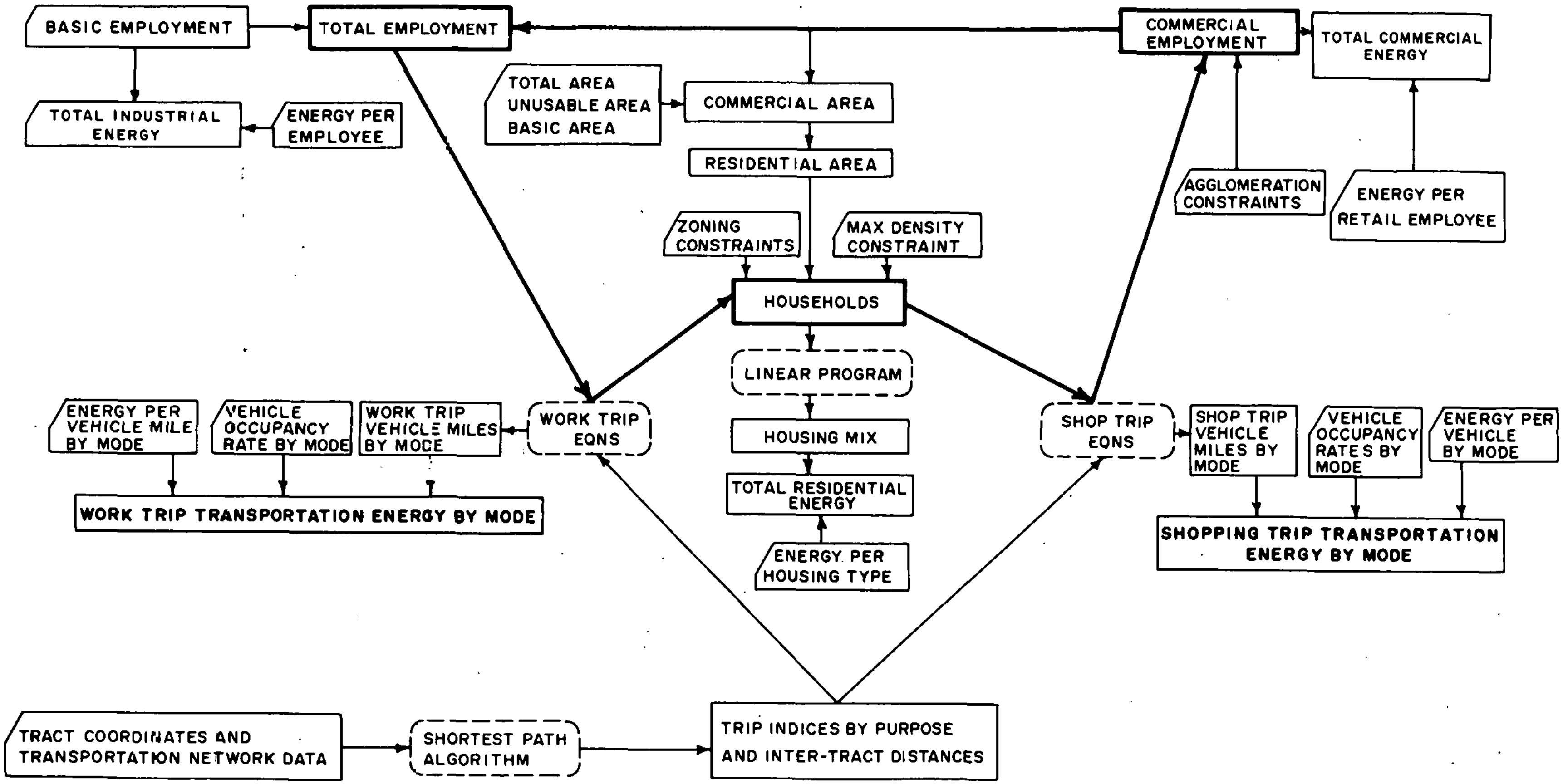


Figure 2. Land use and energy utilization model.

old and new housing stocks for which energy demands differ significantly. This facilitates examining the impact of the single/multifamily housing mix, whose complexity is represented in residential zoning-employment-travel interactions in the spatial allocation process. A linear program is utilized to establish the housing mix in each tract, in which the objective function expresses preferences for each type of housing in the tract and the constraints reflect zoning restrictions and land availability. Commercial sector energy is similarly associated with different types of retail activity. Industrial sector energy is determined through basic industrial employment in the region.

Transportation energy is determined directly in the model. Since the actual spatial allocation is tempered by zoning and agglomeration factors, the resulting land use configuration reflects the "constrained preferences" of residents with respect to travel. Actual industrial-residential-commercial travel assignments by tract, trip distribution for different purposes, and vehicle occupancy rates are utilized in the calculation of passenger miles of travel and energy consumption.[30] Modal split may be integrated into the model through specific grid assignments with alternative modes of transportation. Overall, the spatial land use configuration both determines and is determined by the transporation network so that travel patterns and associated energy demand are explicit.

Land Use Submodel

The development of a land use configuration within the submodel is straightforward. For convenience, a summary of required input variables, parameters, and output variables is shown in Table 1. The region of interest is subdivided into smaller parcels of land called "tracts" which, for good resolution and compatibility with the local shop trip distribution functions, should be taken to be several square miles in area.

Total employment in tract i, $E_i$, is the sum of basic employment, $E_i^B$, plus commercial employment, $E_i^{cK}$. Three types of commercial employment are differentiated to reflect the different travel patterns and economics of scale required. Total employment is given by:

$$E_i = (\sum_{K=1}^{3} E_i^{c_K}) + E_1^B \qquad (1)$$

Initially, the simulation begins with no commercial activity in the tracts so that $E_j^{cK} = 0$ for every commercial type, and all employment in the tracts consists of basic industrial employees. Employment in tract i creates a need for residential units in tract i and surrounding tracts, j. The number of households generated in tract j as a result of employment in tract i is g $E_i T_{ij}^W$, where g is a normalization constant and $T_{ij}^W$ is the work "trip index" which measures the propensity for travel from residential sites in tract j to worksites in tract i. For the moment, we need only note that the trip indices $T_{ij}^W$'s are decreasing functions of the distance between tracts i and j which results in a decrease of residential units in tracts more remote from employment opportunities. A complete discussion of the computation of work and shop trip indices ($T_{ij}^W$ and $T_{ij}^{c_K}$ respectively) appears in the transportation submodel section.

The number of households in a particular tract j is determined by location preference expressed in the trip index and by zoning restrictions. The accessibility of residential areas in tract j from all work sites gives households:

$$H_j = g \sum_{i=1}^{N} E_i \cdot T_{ij}^W \tag{2}$$

where N is the total number of tracts in the region and $H_j$ represents the number of households that would prefer to locate in tract j. However, zoning restrictions act to limit the maximum residential density achievable in each tract to

$$H_j \leq A_j^H Z^H{}_j \tag{3}$$

where $A_j^H$ is the area available for residential use in tract j and $Z_j^H$ is the maximum residential density permitted for tract j. If this residential zoning constraint were to be violated by the number of households which would prefer location in a tract, then the number of households, $H_j$, is set to the maximum permitted by equation (3) and the excess households are redistributed subject to (a) work travel preferences ($T_{ij}^W$) and (b) the amount of residential land remaining vacant in other tracts.

Residential energy demand depends on the housing mix in each tract, or the proportion of different types of residential structures (single family detached, single family attached, multi-family, low rise, high rise). Since the mix is affected by the zoning ($Z_j^H$), a linear programming formulation was used to select the housing mix in each tract. If $H_j$ is the total number of households of structural type m in tract j then the formal linear programming formulation is given by:

$$\text{Maximize } A = \sum_{m=1}^{5} h_m H_j^m \tag{4}$$

subject to:

1. The total number of households in tract j must be consistent with the number of households found from equations (2) and (3) above.

$$H_j = \sum_{m=1}^{5} H_j^m \tag{5}$$

2. The area used in each tract for housing construction cannot exceed the total zoned area available for residential use. If $q^m$ is the land area required (lot size) for each residential unit of type m, then

$$\sum_{m=1}^{5} q^m H_j^m \leq A_j^H \tag{6}$$

3. Zoning restrictions. Zoning restrictions constrain the number of housing units of each housing type. If each $f_m$ is the fraction of land within the tract which is zoned for each type "m" housing, then

$$H_j^m \leq f_m A_j / q_m \tag{7}$$

where, for feasilibity, we require

$$\sum_{m=1}^{5} f_m \geq 1 \tag{8}$$

The coefficients in the objective function, $h_m$, may be selected to favor low density housing or to optimize any other linear utility function involving the number of households of each structural type. Once the proportions of different housing types are established, energy intensity factors may be utilized to determine energy demands for the residential sector.

The market activity for commercial services of all types is generated by both home-based and work-based shopping trips. Work-based shop trips are assumed to be walking trips which occur only within the tract of employment. On the other hand, commercial employment to support residential development in tract i is determined by a trip index $T_{ij}^{c_K}$, which expresses travel preferences for shopping. Commercial employment in tract j is then given by:

$$E_j^{c_K} = b^{c_K} \{d^K E_j + c^K \sum_{i=1}^{N} H_i \cdot T_{ij}^{c_K}\} \quad K=1,2,3 \tag{9}$$

TABLE 1

LAND USE SUBMODEL

Input Variables

| | |
|---|---|
| $A_j$ | Total area in tract j |
| $A_j^U$ | Unusable area in tract j |
| $A_j^B$ | Basic industry area in tract j |
| $E_j^B$ | Basic industrial employment in tract j |
| $T_{ij}^W$ | Work trip indices between sites i and j |
| $T_{ij}^{c_K}$ | Shop trip indices between sites i and three types of shopping (K=1,2,3) |
| $Z_j^H$ | Maximum residential density permitted in tract j |
| $Z^{c_K}$ | Minimum number of employees required in any tract for retail type $c_K$ (K=1,2,3). Economy of scale. |
| $C_m$ | Housing preferences for structural type m |
| $r_j$ | Fraction of usable land permitted for commercial use |

Parameters

| | |
|---|---|
| $a^{c_K}$ | Number of employees of type $c_K$ required per household (defaults may be changed) |
| $b^K$ | Normalization constant computed internally |
| g | Normalization constant computed internally |
| $c^K$ | Constant indicating relative importance of home based shop trips in creating retail employment of type $c_K$ |
| $d^K$ | Constant indicating relative importance of work based shop trips in creating retail employment of type $c_K$. $c^K + d^K \leq 1$ is imposed. |

TABLE 1 (continued)

| | Definition or Purpose or Function |
|---|---|
| $q^m$ | Area per household of structural type m |
| $e^{c_K}$ | Number of acres per retail employee of type $c_K$ required |
| $f$ | Inverse of labor force participation rate |
| $f_m$ | Fraction of total area in tract permitted to be of structural type m |
| | Output Variables |
| $E_j^{c_K}$ | Commercial employment of type $c_K$ and tract j |
| $A_j^c$ | Total commercial area in tract j |
| $H_j$ | Number of households in tract j |
| $A_j^H$ | Area available for residential use |
| $H_j^m$ | Number of households of structural type x in tract j |
| $E_j$ | Total employment in tract j |

where $b^K$ is a normalization constant. The parameters $c^K$, $d^K$, which indicate the relative importance of home-based shop trips and work-based shop trips respectively satisfy $c^K + d^K = 1$.

The total employment of retail type $c_K$ in the region is assumed to be proportiaonl to the total number of households in the region. That is, if it represents the regional total for households, and if $a^{c_K}$ is the labor participation rate for employees of retail type $c_K$, then

$$E^{c_K} = a^{c_K}H \tag{10}$$

The commercial employment of type $c_K$ in tract j given in equation (9) is required to satisfy two additional conditions. First, a sufficiently high level of demand for commercial activity of retail type $c_K$ is required in a tract to make the actual construction of that retail type profitable. This agglomeration constraint takes the form

$$E_j^{c_K} \begin{cases} \geq Z^{c_K} & \text{if } E_j^{c_K} \geq Z^{c_K} \\ = 0 & \text{if } E_j^{c_K} < Z^{c_K} \end{cases} \tag{11}$$

The land which must be allocated for commercial purposes is a function of the employment of each commercial type $E_j^{c_K}$. If $e^{c_K}$ is the gross area required per employee of retail type $c_K$, then the area required for commercial use in tract j is

$$A_j^C = \sum_{K=1}^{m} e^{c_K} E_j^{c_K} \tag{12}$$

However, the area actually used for commercial purposes in tract j is further restricted by the area actually available for commercial use after unusable land $A_j^U$ have been withdrawn, or

$$A_j^C \leq r_j (A_j - A_j^U - A_j^B) \tag{13}$$

where $r_j$ is the fraction of available land which is zoned commercial. Values for $r_j$ determine the interspersion of commercial and residential activities.

The acreage available for residential use is that which has not been utilized for other purposes.

$$A_j^H = A_j - A_j^U - A_j^B - A_j^C \tag{14}$$

Equations (12), (13), (14), establish a priority on land use; basic industry has first priority, followed by commercial and finally residential activity.

Regional conditions on employment and total number of households are reflected in the normalization constants g and $b^{c_K}$ of equations (2) and (4). The total number of households is the product of the inverse of the regional labor force participation rate f and the total employment,

$$H = \sum_{j=1}^{N} H_j = f \sum_{j=1}^{N} E_j \tag{15}$$

Transportation Submodel

The transportation submodel serves two purposes. First, it provides the "trip indices" $T_{ij}^{c_K}$ and $T_{ij}^{W}$ to the land use model (equations 2 and 4) for the spatial allocation of residential sites relative to employment centers and of commercial activity relative to residential development. Second, it uses the spatial distribution of residences, employment, and commercial activity to compute vehicle mileage for work and shop purposes.

The trip indices $T_{ij}^{W}$ and $T_{ij}^{c_K}$ express the aggregate preference for travel between tracts i and j and depend upon the accessibility or difficulty of travel between these tracts. They are calculated on the basis of trip distribution functions, such as that shown in Figure 3, which reflect the fact that fewer people will travel to tracts less accessible from their place of work or residence. In the original version of the Lowry model, the trip indices $T_{ij}^{W}$ and $T_{ij}^{c_K}$ were functions only of the distance $d_{ij}$ between tracts i and j:

$$T_{ij}^{W} = f^{W}(d_{ij}) \tag{14}$$

$$T_{ij}^{c_K} = f^{c_K}(d_{ij}) \quad K = 1,2,3 \tag{15}$$

where, for example, the functions $f^W$ and $f^K$ take the form of inverse polynomials:

$$f^W(x) = \frac{1}{2\pi x\ (C^W + B^W x + x^2)} \tag{16}$$

The constants $C^W$ and $B^W$ are derived by attempting to select those $C^W$ and $B^W$ for which the function in equation (16) "best fit the data" (see figure 3). However, in the Land-Use-Energy Simulation Model, time of travel is utilized as the variable in trip distribution functions. The trip indices are determined by the combination of distance and speed on the transportation network.

The computation of work trip and shop trip mileage is done within the context of the land-use model and is conceptually straightforward. Travel takes place over a uniform network of local roads, overlaid with a system of high-speed limited access highways or mass transit. People are assumed to follow the shortest-time path between any two points. Consequently, initial data to this portion of the sub-model consists of the grid coordinates of the centroids of all tracts. Time-of-travel between pairs of tracts is initially defined as distance times the average local road speed. Highways and/or mass transit are then introduced by reducing time-of-travel between pairs of tracts accessible to the highway or transit system. A modified Floyds[31] algorithm is used to compute shortest-time paths between all pairs of tracts along with the associated distance.

Since the land-use model creates for each employment site a spatial distribution of residential housing around that employment site consistent with accessibility and zoning conditions (equations 2 and 3), the home-to-work distances are known explicitly. Equation (2) gives the number of employees employed at i and living at j.*

$$N_{ij} = (g/f)E_i T_{ij}^W \tag{18}$$

The daily, one-way work-trip passenger miles from i to j is then

$$PM_{ij} = d_{ij}(g/t)E_i T_{ij}^W \tag{19}$$

where $d_{ij}$ is the distance (calculated as above) between tracts. The annual work trip mileage is then

$$V^W = \frac{2m^W}{fp} \Sigma_i \Sigma_j d_{ij} E_i T_{ij}^W \tag{20}$$

where $m^W$ is the number of working days in a year, and p is the automobile occupancy rate for work travel.

*This is modified by a proportionally constant for saturated tracts j. See (9)

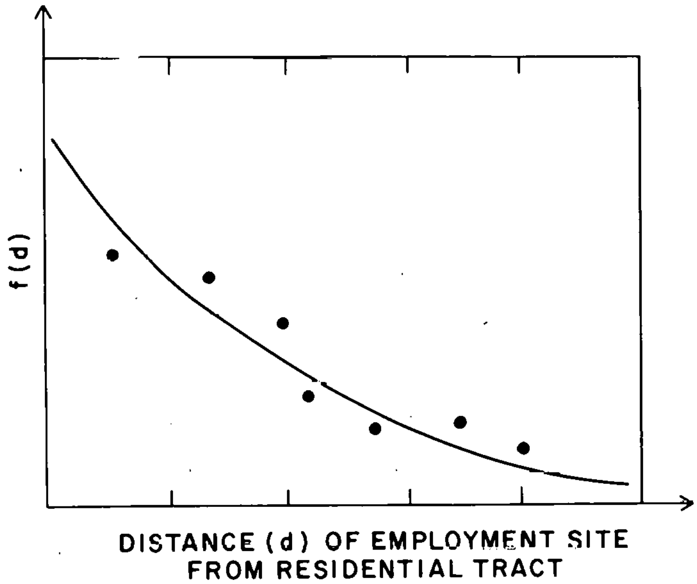


Figure 3. Trip distribution function.

TABLE 2

TRANSPORTATION SUBMODEL

| SYMBOL | DEFINITION OR PURPOSE OR FUNCTION |
|---|---|
| | **Input Variables** |
| $x_i, y_i$ | Grid coordinates of the center of each tract |
| $S_{ij}$ | Speeds of highway links between accessible tracts |
| | **Parameters** |
| $s_o$ | Average local road speeds |
| $m^K$ | Number of shopping trips per year per household for shopping purpose K. |
| $m^W$ | Number of working days per year |
| p | Automobile occupancy rate for worktrip travel |
| $C^W, B^W, {}^cC^K, {}^cB^K$ | Calibrated parameters in the trip-distribution function for work and shop |
| | **Output Variables** |
| $T_{ij}^W$ | Work-trip indices between all pairs of tracts |
| $T_{ij}^{cK}$ | K = 1,2,3. Shop trip indices between all pairs of tracts |
| $d_{ij}$ | Distances between all pairs of tracts (over shortest time-of-travel route) |
| $V^W$ | Vehicle-miles for worktrips yearly |
| $V^S$ | Vehicle miles for shopping yearly |

Shopping trip mileage is computed from the final distribution of residential and commercial activity in a slightly different manner. Households are assumed to make a certain number of trips annually for each of the three types of shopping. The lengths of these trips were derived by examining the opportunities for shopping of each type relative to each residential site and dividing the households shopping trips among these opportunities according to their accessibility. If $m^K$ is the number of shopping trips per year per household for type K shopping, and $H_i$ the number of households in tract i, the total number of shopping trips for purpose K from i is $m^K H_i$. These shopping trips are divided among neighboring tracts which have type K commercial activity, that is, for which $E_j^{C_K} \neq 0$) according to their accessibility. The number of trips from i to j for purpose K is then

$$N_{ij}^K = \left( \frac{T_{ij}^{C_K}}{\Sigma_{\ell=1}^N \; \delta_\ell \; T_{i\ell}^{C_K}} \right) m^K H_i$$

where $\delta_\ell = \begin{cases} 0 & \text{if } E_j^{C_K} = 0 \\ 1 & \text{if } E_j^{C_K} \neq 0 \end{cases}$

The annual shopping trip mileage is, therefore,

$$V^S = \Sigma_i \Sigma_j \Sigma_K \; d_{ij} N_{ij}^K$$

Energy Submodel

The energy submodel computes the energy requirements of the land use configuration generated by the submodels above. Its input variables, parameters, and output variables are listed in table 3.

The extent of the delineation of the specific land use activities and characterization of the energy demands for separate land use activities in the model depends upon several factors. On the one hand, we wish to deliberately restrict the level of disaggregation since no point is served by a model yielding a level of detail that the land use planner cannot utilize. For example, the planner can, at least in theory, exert some measure of influence over the choice of single family vs. multiple family dwellings, or the density of land use. However, this control generally does not extend to the details of the type of construction used, or the income distribution of the projected population. On the other hand, one should not represent a wide range of demands by a single number. For example, we should aggregate all single family dwellings into one category of land use, only if the distribution of total energy demand of all such dwellings in the region is small compared to the average demand.

The approach we adopt is to employ, in so far as possible, the same sets of land use activities used by land use planners. For any particular set of such activities where the characterization of the energy demands is not sufficiently well defined in the sense given above, we characterize subsets which do satisfy this criterion.

Residential energy is computed on the basis of the mix of structural type in the region.

$$\text{Residential Energy} = \sum_{m=1}^{5} \sum_{j=1}^{n} H_j^m \, e_{H,m} \tag{23}$$

where $e_{H,m}$ is the energy demand of a housing unit of type m.

Commercial energy is computed on the basis of commercial employment and floorspace.

$$\text{Commercial Energy} = \sum_{k=1}^{3} E^{ck} \, S_k \, e_{c,k} \tag{24}$$

Here $S_k$ is the number of square feet of floorspace per commercial employee of type k and $e_{c,k}$ is the yearly energy per square foot.

Industrial energy is computed on the basis of employment, disaggregated into five categories (light industry, medium industry, minimg and metals, paper and chemicals, and synthetics):

$$\text{Industrial Energy} = \sum_{k=1}^{5} E^{B,k} \, e_{B,k}$$

where $E^{B,k}$ and $e_{B,k}$ are the number of basic employees in category k and $e_{B,k}$ is the associated energy demand.

Transportation energy depends on total vehicle miles yearly by mode:

$$\text{Transportation Energy} = \sum_{k=1}^{2} (V^s + V^w) \, G^k \, e_{T,k}$$

where $G^k$ is the fraction of vehicle miles traveled by mode k (k - 1, auto, k = 2 bus) and $e_{T,k}$ is the energy demand per vehicle mile.

Finally, we note that energy intensities are available for a finer disaggregation of the four sectors. These may be used where supporting data is available. For example, disaggregation by age class in the residential sector is possible.

Table 3

ENERGY SUBMODEL

| Symbol | Definition |
|---|---|
| $e_{H,m}$ | Energy demand per household per year for structural type m |
| $e_{c,k}$ | Energy demand per square foot of floorspace for commercial structure of type k |
| $S_k$ | Square feet of floorspace per employee, commercial type k |
| $e_{B,k}$ | Energy demand per industrial employee type k |
| $e_{T,k}$ | Energy demand per vehicle mile, mode k |

D. Calibration

The Long Island Nassau-Suffolk region, which is representative of the rapidly growing suburban fringe of many of the nation's cities, served as a testing ground for the methods and concepts. The current population of the Nassau-Suffolk region shown in figure 4 is approximately 2,500,000 with a further population increase of 1,500,000 expected by the year 2000. The region now contains a mix of areas of high population density close to New York City and semi-rural areas in the eastern tip of Long Island. Areas that were only entirely agricultural are being taken over by housing developments, shopping centers, and industrial parks. At present, the overall pattern of land use in the Nassau-Suffolk region consists of mostly detached single-family homes with a variety of retail types, offices, and industrial parks scattered along major highways and interconnecting roads. With current residential, commercial, and industrial sites so thinly interspersed and no basic system of public transportation, the private automobile forms an essential part of the "Long Island" life-style.

The Land Use-Energy Simulation Model requires the following categories of data to provide an adequate representation of regional characteristics:

1. Land Use Submodel: industrial employment
   industrial area
   total area
   unusable area
   regional economic and land use parameters

2. Transportation submodel: work trip function parameters
   shop trip function parameters
   occupancy rates and data on numbers of work and shopping trips annually

3. Energy submodel: energy per dwelling unit of each structural type
   energy per sq. ft. of commercial floorspace
   energy per industrial employee of each type
   energy per vehicle mile for each mode

A list of the values of land use, transportation, and energy parameters for the Long Island calibration is given in Table 4. While the data demands for the model appear to be substantial, most of such data is commonly and easily available to planning agencies in most regions of the country. The "East End" of the region is two narrow peninsulas. The development of these severly constrained by physical

TABLE 4

PARAMETERS USED FOR LONG ISLAND STUDY

| SYMBOL | DEFINITION | VALUE |
|---|---|---|
| $a^{c_1}$ | | .17 |
| $a^{c_2}$ | Number of employees of type $c_K$ required per household (default may be changed) | .27 |
| $a^{c_3}$ | | .18 |
| $c^1$ | | .5 |
| $c^2$ | | .7 |
| $c^3$ | Relative importance of work based shop trips in creating retail employment of type $c_K$. | .9 |
| $d^1$ | $c^K + d^K = 1$ is imposed. | .5 |
| $d^2$ | | .3 |
| $d^3$ | | .1 |
| f | Inverse of labor force participation rate | .872 |
| $Z^{c_1}$ | | 30 |
| $Z^{c_2}$ | Minimum number of employees required in any tract for retail type $c_K (K = 1,2,3)$. Economy of scale | 200 |
| $Z^{c_3}$ | | 1000 |
| $e^{c_1}$ | | .056 |
| $e^{c_2}$ | Number of acres per retail employee of type $c_K$ required | .037 |
| $e^{c_3}$ | | .0024 |
| $Z_j^H$ | Maximum residential density permitted in tract j in households per acre. | 5 |
| $f_m$ | Fraction of total households in tract permitted to be of structural type m | 1 |
| $C_1$ | | 6 |
| $C_2$ | | 5 |
| $C_3$ | Housing preferences for structural type m $(m = 1,\ldots,5)$ | 2 |
| $C_4$ | | 1 |
| $C_5$ | | .5 |

TABLE 4 (cont.)

| SYMBOL | DEFINITION | VALUE |
|---|---|---|
| $r_j$ | Fraction of usable land permitted for commercial use | 1 |
| $q^1$ | | .33 |
| $q^2$ | | .2 |
| $q^3$ | Area per household of structural type m in acres | .1 |
| $q^4$ | | .07 |
| $q^5$ | | .033 |
| $m^c1$ | | 219 |
| $m^c2$ | Number of shopping trips per year per household for shopping purpose K. | 146 |
| $m^c3$ | | 91 |
| $m^W$ | Number of working days per year | 260 |
| p | Automobile occupancy rate for work trip travel | 1.2 |
| $C^W$ | | 181 |
| $B^W$ | | -2 |
| $C^c1$ | | 1.13 |
| $B^c1$ | Calibrated parameters in the trip-distribution function for work and shop | -1.6 |
| $C^c2$ | | 6.25 |
| $B^c2$ | | -3.0 |
| $C^c3$ | | 13 |
| $B^c3$ | | -4 |
| $e_{H,1}$ | | 119 |
| $e_{H,2}$ | Residential energy demand ($10^6$ Btu) | 88 |
| $e_{H,3}$ | (Old stock) | 85 |
| $e_{H,4}$ | | 78 |
| $e_{H,5}$ | | 65 |

TABLE 4 (Cont.)

| SYMBOL | DEFINITION | VALUE |
|---|---|---|
| $e_{H,1}$ | | 109 |
| $e_{H,2}$ | Residential Energy Demand ($10^6$ Btu) | 95 |
| $e_{H,3}$ | (New Stock) | 88 |
| $e_{H,4}$ | | 84 |
| $e_{H,5}$ | | 75 |
| $e_{C,1}$ | | 173 |
| $e_{C,2}$ | Commercial Energy Demand ($10^3$ Btu/sq.ft.) | 218 |
| $e_{C,3}$ | (Old Stock) | 142 |
| $e_{C,1}$ | | 155 |
| $e_{C,2}$ | Commercial Energy Demand ($10^3$ Btu/sq.ft.) | 2.8 |
| $e_{C,3}$ | (New Stock) | 121 |
| $S_1$ | | 1585 |
| $S_2$ | Sq.ft. site space/employee | 1047 |
| $S_3$ | | 67.6 |
| $e_{B,1}$ | | .12 |
| $e_{B,2}$ | Industrial Energy Demand ($10^9$ Btu/employee) | .32 |
| $e_{B,3}$ | | 1.17 |
| $e_{B,4}$ | | 6.00 |
| $e_{B,5}$ | | |
| $e_{T,1}$ | Transportation Energy Demand | 9180 |
| $e_{T,2}$ | (Btu/Vehicle Mile) | 3150 |

limitations of water supply preservation of marine resources and farmland protection programs. Consequently, only limited growth is expected within the time frame for the regional study in the applications section of this report and the east end areas were not included in calibration of the model.

Land use data was obtained from the Nassau-Suffolk Bi-County Regional Planning Commission for a grid system of three mile square tracts (see figure 4). Land use data in 16 categories was reduced to total area, industrial area, commercial area, and a category for undevelopable or unusable acreage including water area, parks and recreation, etc. Employment and population data were available from county publications, but required additional disaggregation to be compatible with the three mile tract system.

Land use, employment, and population information were taken from the years 1970-1975 but were adjusted to the common base year 1970 for purposes of model calibration. However, it should be noted that the regional boards' land use data includes information for 1968, 1975, and 1985. Comprehensive Plan estimates should prove useful in assessing questions of regional growth. Since it is possible to force the model into very specific patterns of development by a poor choice of zoning, selecting maximum residential density constraints requires care. We set the maximum density constraint $Z_j^H$ to a single value for all tracts, which constrains population densities in western Nassau County near New York City but otherwise permits the allocation of the remaining population without constraint.

Basic employment was composed of three components. Industrial and mining activities employ approximately 20% of the regional workforce. An additional 25% are employed in New York City, which is treated as a worksite but is otherwise outside the boundaries of land use interactions in the model. Certain federal and state agencies and institutions, which together employ only a small percentage of the region's workforce, were also included as basic employment.

In addition to the detailed employment data, regional totals of retail employment and land use by type, as well as average residential land use figures were used to develop the land use parameters shown in Table 4. Certain parameter values (such as the agglomeration constraint values $Z^k$) can be carried over from the original Pittsburgh calibration of the Lowry model.

Few detailed transportation studies were available for the Long Island region. The most recent such study for work-trip travel patterns dates from 1963.

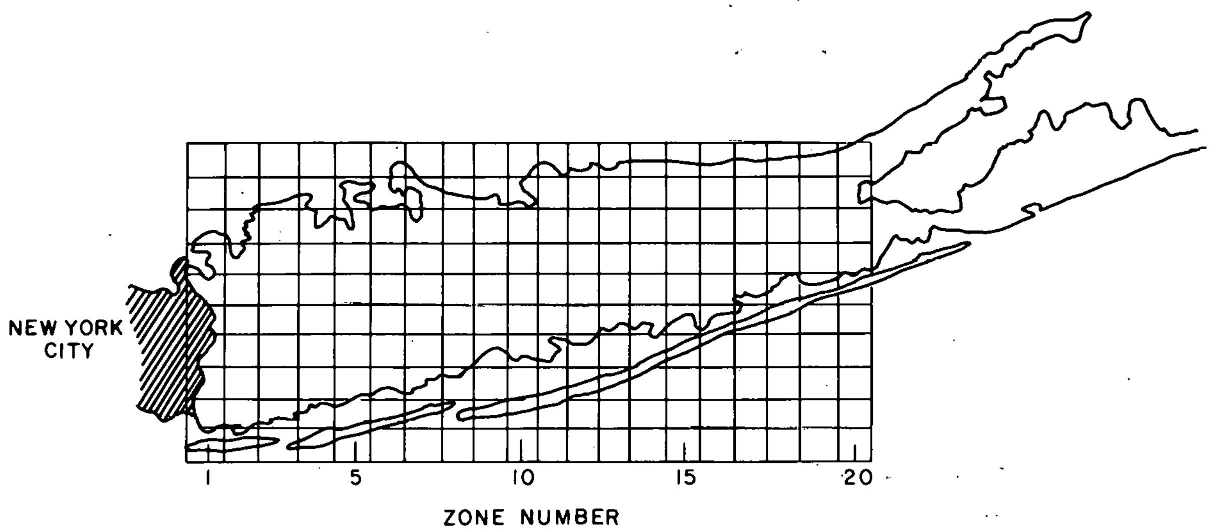


Figure 4. Grid system for the Nassau-Suffolk case.

Virtually no in-depth studies of shop trip travel patterns have been done, though some business district trip information was available from surveys of parking needs and residential location of autos relative to the individual shopping districts under study. However, studies of other regions of the country do provide some background on average trip lengths and trip distributions which can be used in conjunction with region-specific data to provide an overall calibration of the model. For this application and calibration of the model, the trip indices were taken to be functions of distance, and were established from trip-length data.

The energy intensity-factors appropriate for the Long Island area were taken from "The Planners' Energy Workbook", which describes techniques and data sources to establish the energy intensity associated with land use activities for any region of the country. The characterization of energy shown in table 4 - by structural type for residential uses, e.g. - is convenient for analyzing land use as a determinant of energy demands. However, to explore the effect of regional energy supplies upon land use and other more detailed energy system interactions requires further disaggergation of end use to reflect details of fuel consumption patterns, such as electric load curves.

Overall, the model creates a spatial land use configuration very much like that existing in the region of 1970.* The total residential population in each zone of the region (the vertical "strips" numbered in Figure 4) is plotted in Figure 5 showing the model's results and figures extracted from 1970 census data. Total commercial land, again by zone, is shown in Figure 6, and compared to 1975 Planning Commission data. In Figure 7, the commercial employment by zone of worksite is shown.

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*The model was implemented on the UNIVAC U1100 using the UNIVAC ASCII Fortran compiler. This machine is reported to be 2 or 3 times faster than the IBM 370/155, but slower than the CDC6600 or 7600. Computation time on the UNIVAC for the land use and energy portions of the model for a region divided into 300 tracts is about 2½ - 3 minutes. The computation time is basically quadratic in the number of tracts, but computation time also varies widely depending on the data involved. Memory requirements are estimated at less than 25,000 words. This is more a product of the length of the code (approximately 2,000 statements) than the need to store data.

The addition of the transportation model adds considerably to time and core requirements. The algorithm we are presently using is cubic in the number of tracts and takes 9 minutes for 300 tracts. As was mentioned earlier, this algorithm produces $2n^2$ indices representing time-of-travel and distance. If $n=300$, this number is 180,000. These numbers are stored as indices ranging from 0 to 127, and packed five to a 36-bit UNIVAC word, so that 36,000 additional words are required.

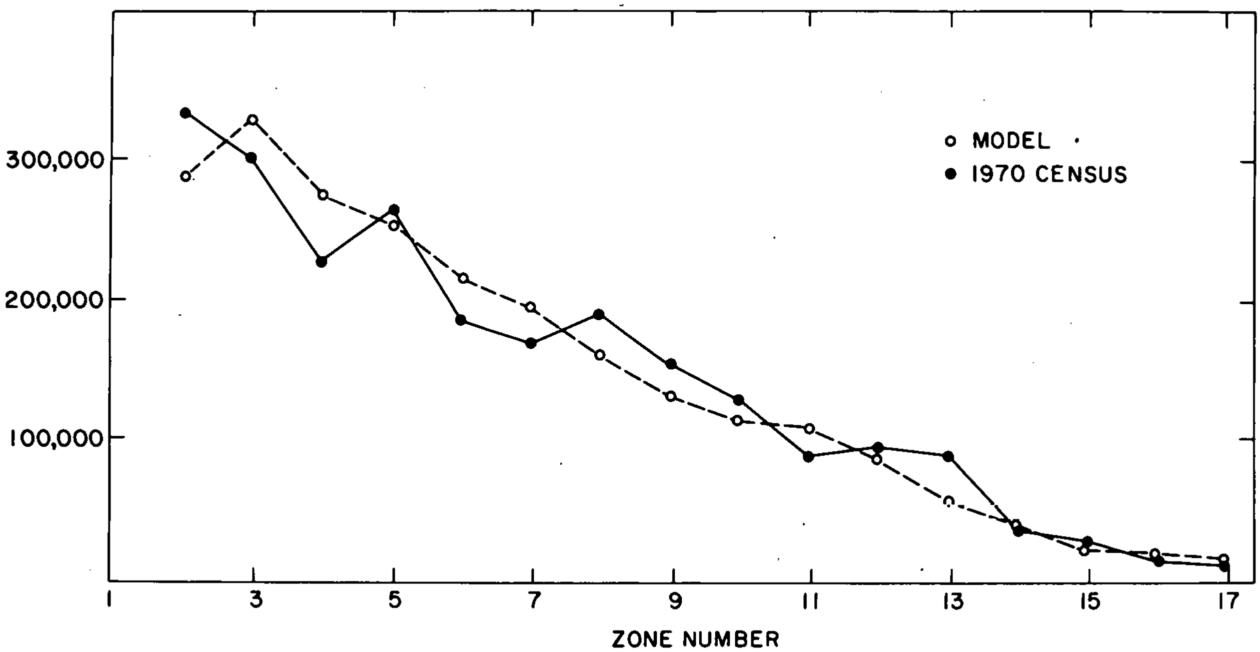


Figure 5. Population by zone.

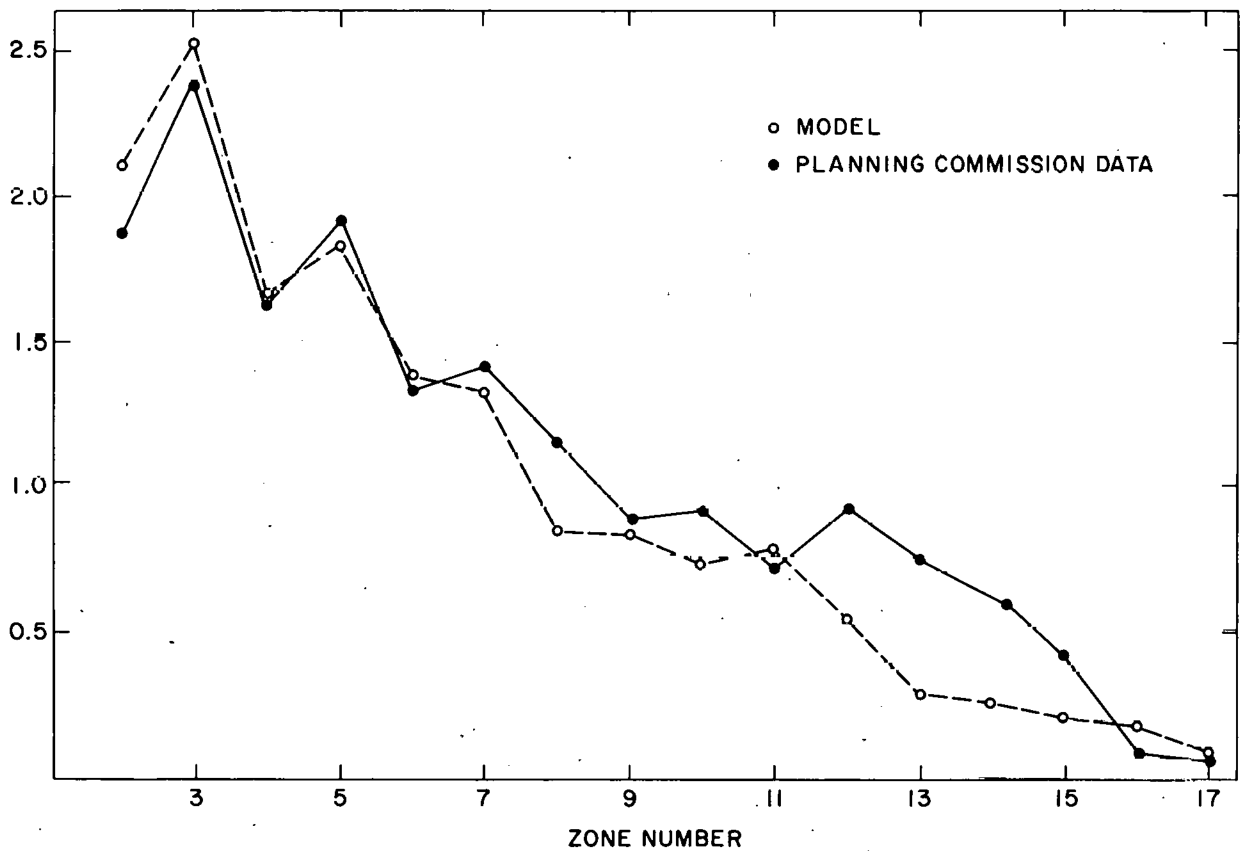


Figure 6. Commercial land by zone (thousands of acres).

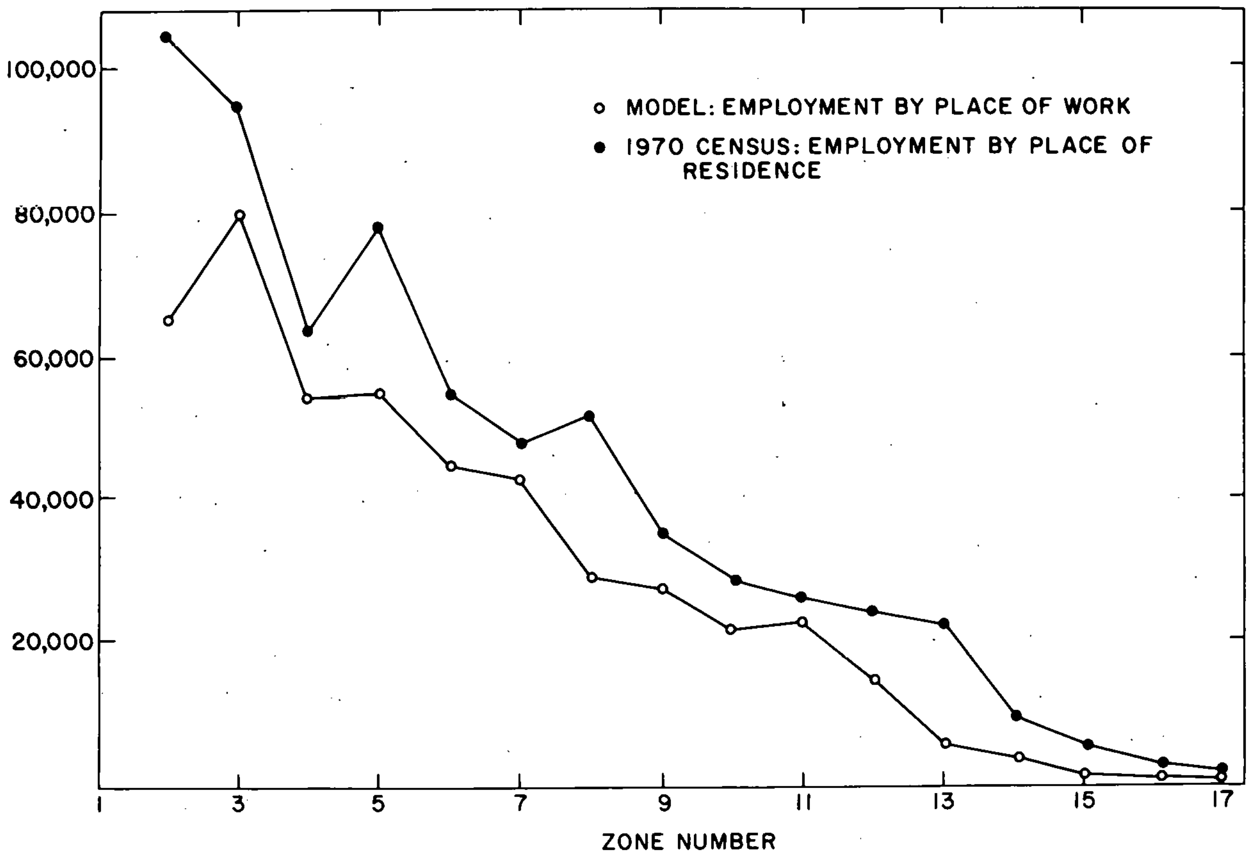


Figure 7. Commercial employment.

Also shown are 1970 census figures on the commercial workforce by place of residence. Census data on employment by place of work cannot be utilized for calibration because employees in these tabulations were allocated to company headquarters rather than actual location of work. Comparisons of residential acreage and other calibration measures follow similar patterns. Both numbers of persons (households, employees, travelers) and land areas allocated to different activities follow aggregate regional patterns.

The model also replicates specific detail in smaller groups of tracts such as concentrations of commercial activity near large residential populations. Figure 9 shows a scatter-plot of commercial acreage figures from Bi-County data and model results for two-tract areas. Again, the agreement between model results and regional data is quite good. A part of the differences between the model and regional data is inconcistency in the tract land use data base itself.

In Figure 8, the average work-trip length derived from the model for areas of Long Island is shown. Also shown are values calculated from the Long Island Journey-to-Work Report (1963). The averages were taken over areas corresponding approximately to zones 1-3, 4-5, 6-8, 9-13, and 13-20. Both length of trip and the trend in worktrip lengths as we move outward from New York City are in relatively good agreement.

Finally, Table 5 gives a comparison of the model's energy demands with estimates derived from a Brookhaven National Laboratory study for the Long Island Lighting Company, based on utility and other supply-side data.

The industrial development specified in the model was entirely light industry, whereas there are small amounts of more energy intensive industry in the region.

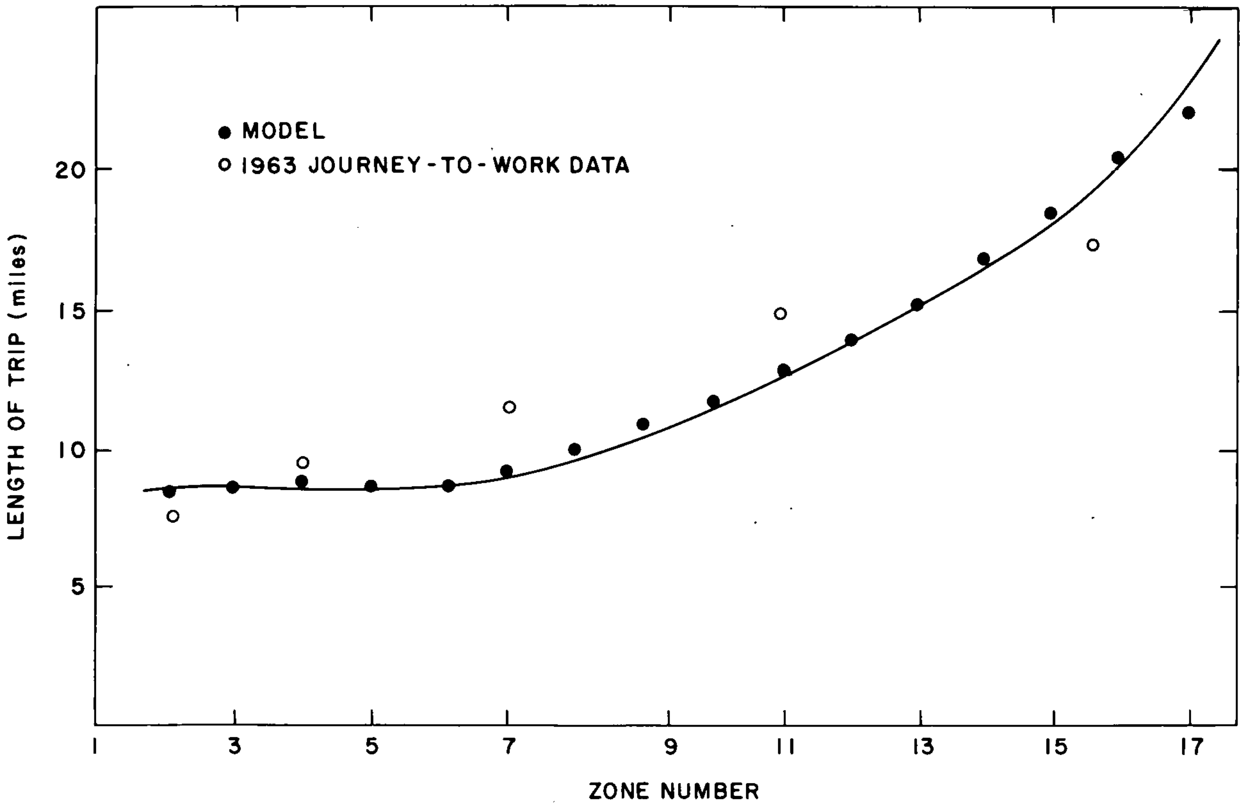


Figure 8. Worktrip lengths.

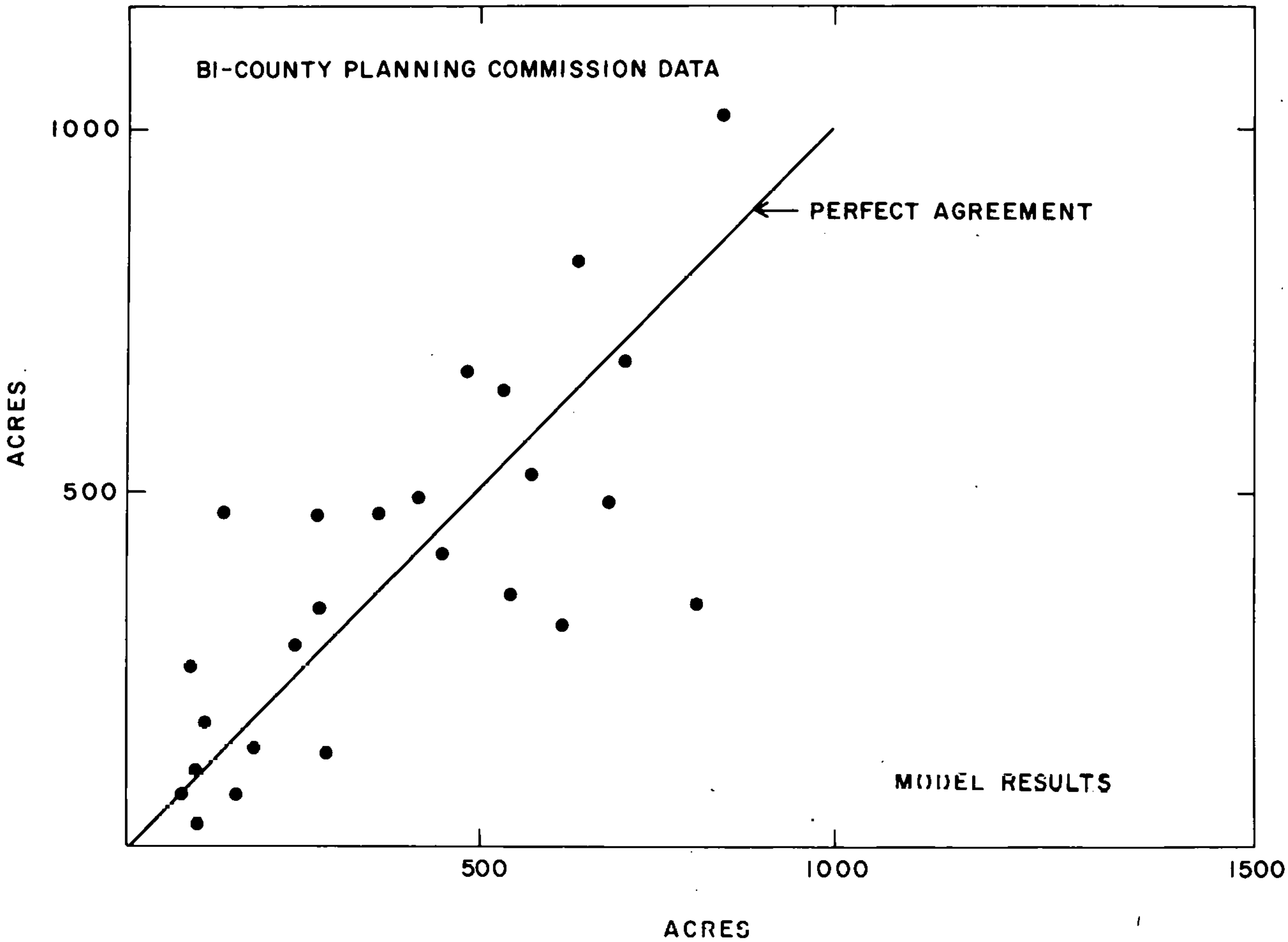


Figure 9. Scatter-plot of commercial acreages for 2-tract sections.

TABLE 5

ENERGY COMPARISONS ON YEARLY BASIS

| LAND USE SECTOR | ENERGY PREDICTED BY MODEL ($10^{12}$ BTU) | ENERGY DERIVED IN REPORT[29] ($10^{12}$ BTU) | % DIFFERENCE |
|---|---|---|---|
| Residential | 89. | 84.1 | +5.5 |
| Basic | 24.6 | 28.9 | -15 |
| Retail | 69.1 | 63.9 | 8 |
| Transportation* | 44.1 | 47.1 | -6 |

*This includes auto travel for purposes of work and shop and incorporates auto efficiencies at end use. The model in its current form does not include social recreationsl trips since these trips are not, in general, based solely on employment levels and households but also on the peculiar local geographical features internal and external to the region of study. It has been found [35] that transportation energy consumption for the Northeastern Region consists of:

70% - Personal Auto
15% - Truck Freight
5% - Inter-City Rail-Bus-Air
8% - Other Freight
2% - Miscellaneous

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## III. APPLICATIONS

The computer model was developed as a tool for two specific types of applications. First, specific regions of the country can be analyzed to estimate the energy demands of the region under various growth scenarios. The object here would be to analyze the long term land use and energy implications of changes in residential zoning, commercial restrictions, and basic industrial sitings. In the second case, the computer model is intended to study the generic relationships between energy utilization and "urban form".

### A. Basic Industrial Siting

In this section, we describe the preliminary findings of several computer runs of the model which are aimed at exploring the generic relationship between energy demand and "basic" industrial employment dispersion in an urban sprawl situation. The results are suggestive and indicate the need for further exploration with the model before definitive statements can be made concerning the magnitude and direction of the interactions.

The model has been applied to a prototypical region with 675 square miles. The total basic employment in the region was held fixed but the manner in which it was distributed radially around a preselected grid was allowed to vary according to the function

$$E_r^B = E(r_o)e^{-r/r_o} \tag{26}$$

where r is the radial distance from the central grid and $r_o$ is a constant which determines the dispersion of basic employment in suburban regions. $E(r_o)$ is a constant with respect to r but is selected to obtain the proper total basic employment in the region. If $r_o$ is very large ($r_o \geq 100$ say), then the basic employment approaches a uniform distribution, however, as $r_o$ approaches zero, the basic employment becomes more concentrated in a "central business district". (See Figure 10 below). Notice that the scales used for population density and employment density differ by a factor of four and may mislead the casual reader. In view of this fact, population densities are much higher for the concentrated employment case and decay more rapidly than the less centralized case.

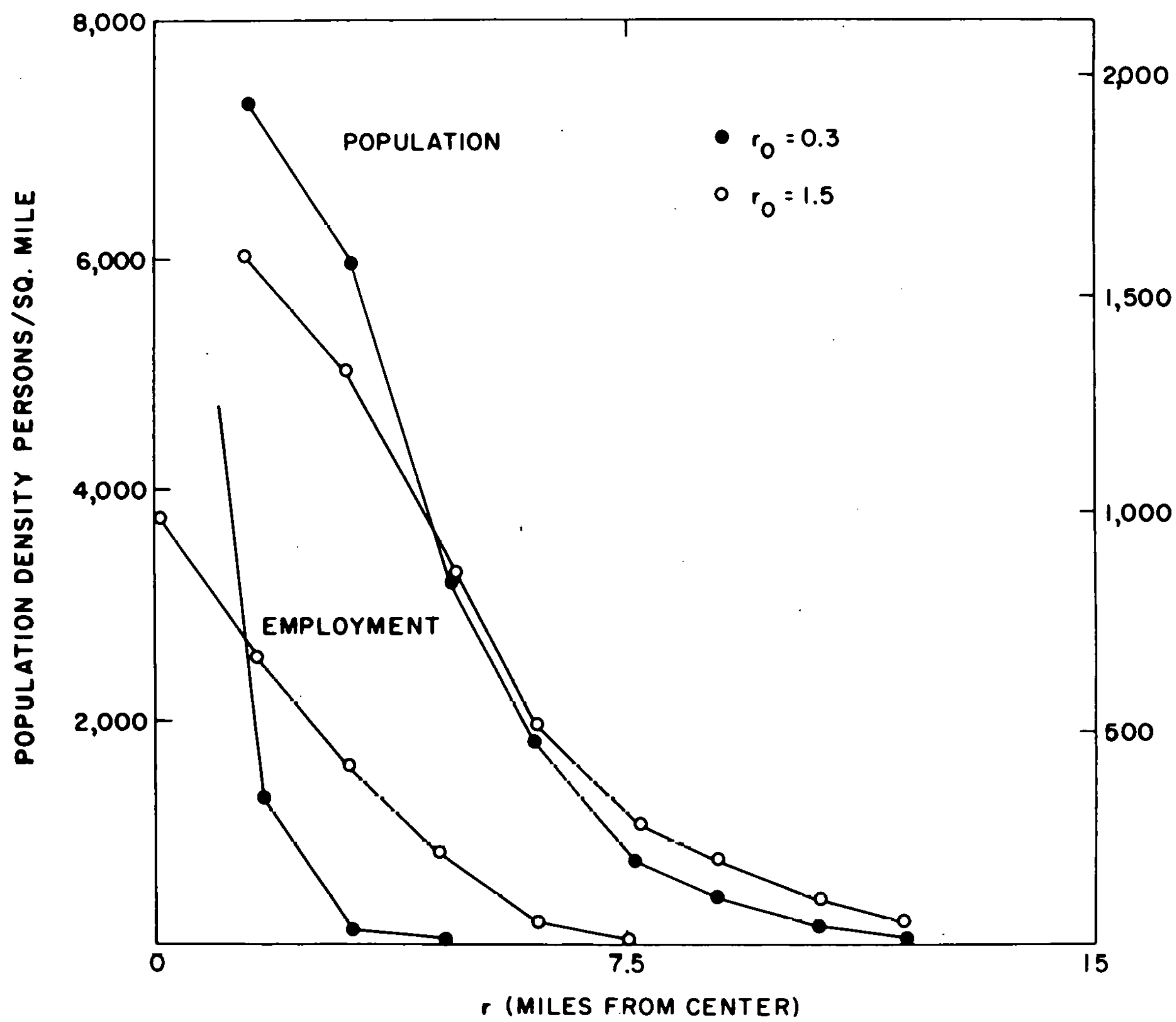
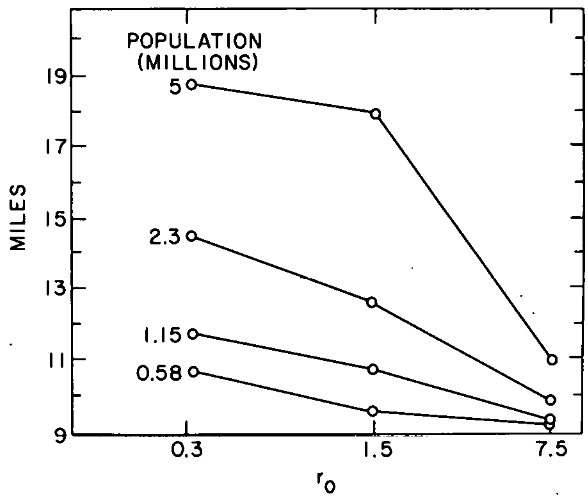



Figure 10. Population and basic employment densities for population (580,000).



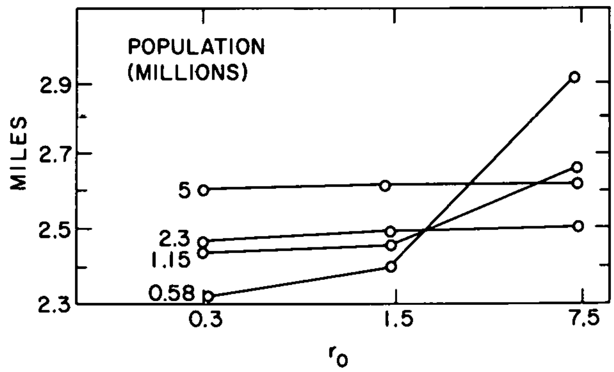




Figure 11a. Total daily work trip mileage per household.

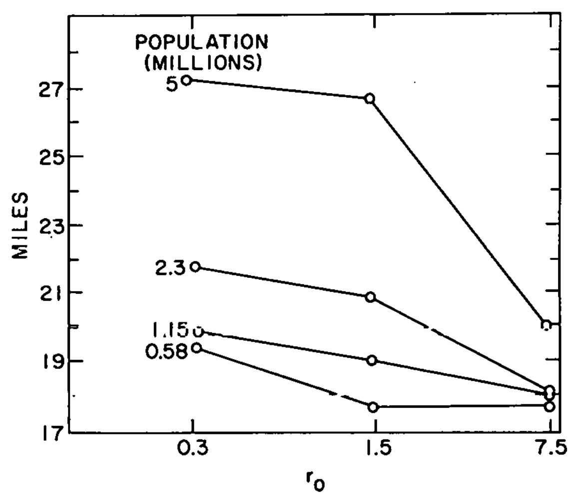



Figure 11b. Total work plus all shop mileage per household.

The residential zoning restrictions were held fixed for all runs with a uniform maximum density constraint $Z_j^H$ roughly equivalent to suburban sprawl. Single family detached and attached homes were permitted with a preference for single family detached homes. Figure 10 illustrates the basic employment distribution and the resulting population distribution. Table 6 summarizes the results of twelve computer runs. The dispersion factor ($r_o$) took on three values ($r_o$ = .3, 1.5, 7.5) for each of four populations (.58 million, 1.15 million, 2.3 million, and 5 million).

Figures 11a and b illustrate the complex trade-off between work- and shopping-trip vehicle miles in each case. Centralized employment ($r_o$ = .3) implies that work trip lengths are relatively long whereas shopping trends tend to remain relatively short. For dispersed employment ($r_o$ = 7.5), i.e., where a central region of high basic employment is surrounded by significant levels of dispersed suburban employment, the graphs imply shorter work-trip lengths but longer shopping-trip lengths. The reason for these shifts appears to be a result of the agglomeration constraints. Lower population densities cannot support commercial development except at a limited number of sites. Overall, the least vehicle miles per household occurs for the case of some modest suburban employment.

It is useful to examine the total annual per capita consumption. Low, widely distributed populations (.58 million people with $r_o$ = 7.5) require 96.9 x $10^6$ Btu/person whereas large centralized populations (5 million people with $r_o$ = .3) require 105.2 x $10^6$ Btu/person. This points to the large potential savings which are achievable through careful choices of land-use patterns in a growing region.

Table 6 indicates that growth in a region can be accomplished with either increasing or decreasing per capita energy consumption. This suggests that existing communities which are rapidly growing have options over the next 20 years leading to either increases or decreases in per capita energy consumption depending on the selected growth strategy.

## B. Suffolk County - A Case Study for Year 2000

Since most future growth on Long Island, both in terms of land-use development and population, is expected to take place in the Island's eastern areas, the focus of this case study is to study land-use-energy interactions under alternative conditions of growth in Suffolk County.

Three regional scenarios were constructed to explore the energy requirements of alternative growth patterns:

TABLE 6

ENERGY PER CAPITA PER YEAR

| POPULATION (millions) | $r_o$ | TRANSPORTATION | RESIDENTIAL | TOTAL |
|---|---|---|---|---|
| | .3 | 32.7 | 32.5 | 105.2 |
| 5 | 1.5 | 31.9 | 32.5 | 104.4 |
| | 7.5 | 23.8 | 32.5 | 96.3 |
| | .3 | 25.6 | 32.9 | 98.5 |
| 2.3 | 1.5 | 24.4 | 33.7 | 98.1 |
| | 7.5 | 20.6 | 33.7 | 94.3 |
| | .3 | 23.8 | 34.4 | 97.7 |
| 1.15 | 1.5 | 22.4 | 34.4 | 96.3 |
| | 7.5 | 20.6 | 35.5 | 96.9 |
| | .3 | 22.8 | 34.9 | 97.7 |
| .58 | 1.5 | 21.2 | 35.1 | 96.3 |
| | 7.5 | 20.6 | 36.0 | 96.9 |

- Urban Sprawl (U.S.)
- Comprehensive Plan (C.P.)
- Growth Centers (G.C.).

Continued urban sprawl and the development of large population centers of concentrated land use and economic activity represent opposite extremes of projected future growth in the Nassau-Suffolk region. Their analysis outlines the extremes of energy consumption patterns associated with land use. On the other hand, the comprehensive plan prepared by the Bi-County Commission[34] provides practical guidelines for regional development consistent with environmental and other factors. In each case, overall population and employment projections remain the same, reflecting estimates for Suffolk County growth to the year 2000:

Suffolk Population and Employment (THOUSANDS)

| | YEAR | |
|---|---|---|
| | 1975 | 2000 |
| Population | 1300 | 2350 |
| Households | 380 | 758 |
| Commercial Employment | 258 | 516 |
| Basic Employment | 178 | 355 |

These alternative land-use scenarios differ primarily in the spatial allocation of basic employment opportunities and zoning constraints imposed upon residential location. A summary of these allocations is given in Table 7. With few exceptions, all other parameters were carried over to the Suffolk cases from the Nassau-Suffolk calibration runs.

In the urban sprawl case, industrial zoning and residential development is assumed to continue according to the pattern that has clearly developed in western Nassau and eastern Suffolk. Residential zoning constraints were established from 1975 land-use. A tract was considered "developed" if its residential density exceeded 2.5 dwelling units per acre. No further residential development of such tracts was permitted.

Industrial growth in the urban sprawl scenario will follow existing patterns so that the spatial distribution of Suffolk's basic employment force remained unchanged, i.e., internal "basic" employment of Suffolk County in 1975 was simply scaled up to the 355,400 basic jobs required to support a population of 2.35 million.

The second scenario is based on the land-use allocation of the comprehensive plan. Commuting to employment opportunities outside the region will not increase significantly over present levels so that the 1975 commuting patterns remain unchanged. (This implies a large increase in internal basic employment which was allocated mainly to middle and eastern Suffolk industrial zones and are described in the comprehensive plan. These industrial areas have good access to residential clusters and "centers".)

The residential density constraints are computed in a straightforward way to be consistent with zoning and residential densities in the 1985 comprehensive plan data. Land designated as vacant, farmland, or parks and recreation was designated as "unusable."

The third case represents an extreme case of clustering in which all new basic employment after 1975 is allocated to four "centers". Commutation is assumed to remain the same as in the comprehensive plan above. Residential siting is constrained to 1975 levels except to within a radius of about six miles of these "centers". Tracts near these "centers" have very high residential-density constraints of 15 dwelling units per acre, allowing low- and high-rise construction. These conditions create four large population "centers", or cities, in the region.

The major energy-related results of these runs are summarized in Table 7. Significant shifts in energy consumption patterns in the transportation sector result from the spatial patterns of basic employment sites in the different growth scenarios. In the urban sprawl case, a large fraction (13% of the work force) must commute from various locations in New York City, more than 20 miles away. The relocation of employment into Suffolk County in the other scenarios not only shortens the work-trip length for those employees whose place of employment has been changed but also for those who continue to commute because of the better availability of housing sites in the western part of the county. For example, the average trip-length for a Queens commuter in the urban sprawl scenario is 35 miles; for the comprehensive plan, it is 25.8 miles. The small reduction in work-trip mileage from the comprehensive plan to the "centers" scenario is significant but not as large as that from urban sprawl to comprehensive plan. Workers employed in the more compact "centers" have shorter trip-lengths than those employed in the industrial corridor of the comprehensive plan.

There is also a significant change in the residential energy consumption caused by the shift away from the single-family homes toward the higher-density types. The housing breakdown in the urban sprawl case is similar to the present breakdown in

TABLE 7
SUMMARY OF SCENARIO RESULTS

| | Case 1 (Sprawl) | Case 2 (C.Plan) | Case 3 (Centers) |
|---|---|---|---|
| ENERGY USAGE ($10^{12}$Btu/YR) | | | |
| BASIC | 42.6 | 42.6 | 42.6 |
| COMMERCIAL | 47.1 | 47.1 | 47.1 |
| RESIDENTIAL | 79.9 | 76.0 | 74.8 |
| TRANSPORTATION+ | 78.7 | 56.3 | 53.4 |
| TOTAL | 248.5 | 222.0 | 217.9 |
| PER PERSON ($10^6$Btu) | 105.6 | 94.5 | 92.7 |
| HOUSING BREAKDOWN (PERCENT) | | | |
| SINGLE FAMILY DETACHED | 89.2 | 69.3 | 65.5 |
| SINGLE FAMILY ATTACHED | 3.8 | 5.4 | 6.7 |
| LOW RISE | 6.7 | 19.4 | 20.5 |
| HIGH RISE | .3 | 5.7 | 2.3 |
| PERSONAL TRANSPORTATION | | | |
| DAILY WORK-TRIP DISTANCE* | 35.8 | 23.8 | 22.6 |
| DAILY SHOP-TRIP DISTANCE** | 14.8 | 14.6 | 14.4 |
| PERCENT DECREASE FROM CASE 1 | | | |
| RESIDENTIAL | | 4.9 | 6.4 |
| TRANSPORTATION | | 28.6 | 32.3 |
| TOTAL | | 10.7 | 12.3 |

+does not include social-recreational or truck; auto travel assumed.

*mileage travelled for work purposes on a weekday per household.

**total average shopping mileage daily per household.

Suffolk and is clearly a result of the zoning imposed. The change in mix occurring in the comprehensive plan case is a result of clustering. Zoning encourages the emergence of clusters in the appropriate locations. Second, residential areas in the comprehensive plan are easily accessible from employment sites.

Commercial and basic energy utilization were intentionally held constant in these runs in order to effect a clear-cut comparison of other factors associated with land-use development patterns.

Two points are noteworthy regarding the overall savings in energy demonstrated under the comprehensive plan and the continued sprawl scenarios. The first is the large potential savings achievable in the transportation area as a result of the careful interspersion of "basic" employment and residential sites (and zoning). Secondly, the bulk of the savings in both the transportation and residential sectors was achieved within the guidelines of the comprehensive plan and under entirely reasonable assumptions. Finally, although the comprehensive plan was not initially designed to produce savings, it is clear that substantial energy benefits result from the creation of clustered and/or compact residential and commercial sectors if accessible from nearby employment sites.

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## IV. FINAL COMMENTS

The land use-energy simulation model proves useful in assessing energy implications of a broad variety of alternative land use patterns which may be considered in the planning process. From the planner's perspective, the issue is not how to achieve energy savings per se. More important is the need to evaluate the energy intensity and fuel mix possibilities which arise in response to alternative land use growth and the ways in which these may inhibit regional development or otherwise cause imbalance between regional energy needs and the national energy system. In this context, the model may be utilized both to explore incremental changes in land use patterns and their impact upon local zoning and to examine overall regional growth strategies.

For regional planning groups which seek to use the model for such analyses, the personnel and fiscal requirements for implementing the model are relatively modest. The region-specific data needs include local zoning, usable land, and basic employment. These are characteristics commonly on file with most planning organizations. Many of the other parameters which influence energy and land use pattern development, such as travel indices, relation between commercial employment and population, energy intensity coefficients, etc. may be easily calibrated for the planner's own area and/or can be carried over from one region of the country to another. In this sense, the choice of variables and preparation of the model was oriented toward its adaptation to planner's needs in their local area.

From the perspective of federal agencies responsible for energy management, there has been too little consideration of the role of land use as a supporting or inhibiting agent in the accomplishment of federal objectives. The land use-energy simulation model can be utilized to explore the generic problems of energy-importing versus energy-exporting regions, as well as of other regional distinctions. Fundamental differences in both physical characteristics and development preferences between such regions lead to sharp distinctions in overall land use patterns. These, in turn, lead to differing associated fuel mix possibilities. Equally important is the need to explore the land use-energy relationships which accompany the commercialization of new technologies. For example, the land use-energy simulation model is a good vehicle for the exploration of land use trends, their compatibility with introduction of the electric car, energy utilization associated with the electric car under a variety of assumptions of its use for work, shopping, and other types of trip purposes, and would provide a better definition of the market areas of these new technologies.

While the focus of this report and FEA grant concerns model development and testing, the model has been applied to a limited extent to the exploratory study of land use and energy utilization generic relationships. The suggestions that such generic relationships exist have important implications for energy and land use policies that warrant further study. For example, transportation energy is found to be determined more by employment and population density gradients than by density itself which is the traditional measure of land use. Trip lengths for the various travel purposes depend primarily upon distance from a city or urban activity center. Also, for the auto-based transportation and zoning typical of our cities, the spread of employment to the suburbs is found to lead to significantly lowered transportation energy consumption. Indeed, the potential energy savings in transportation alone approach fifty percent under reasonable land use patterns suggested by planners. Both the general character of these land use-energy generic relationships and the potential energy shifts inherent in alternative land use patterns suggest further utilization of the model to explore the implications of present U.S. growth trends and alternatives to these present trends which might improve the national energy situation.

There are several extensions of and improvements to the model which would provide a broader capability for land use-energy-environment assessment. For example, the model can be utilized for in-depth study of the impact of a major energy facility. The studies done in connection with Nuclear Regulatory Commission research indicate that the location of a major energy facility brings with it not only new labor force and associated population, but also other economic activities and households who desire to exploit the low tax situation that is likely to be in effect as a result of a new major facility. The existing model can be effectively employed to analyze the energy consumption implications and other implications of community growth under different zoning regulations, under different transportation networks, and under different housing, commercial, and general urban design parameters. Additions to the model of liquid, solid, and air emissions related to the land use activity measures would be straightforward, as would augmentation of dispersion models for these pollutant emissions. The model could then be utilized to pinpoint different environmental and health implications. Finally, the model is such that it would give a continuous accounting of population exposure to nuclear hazard as the region grows.

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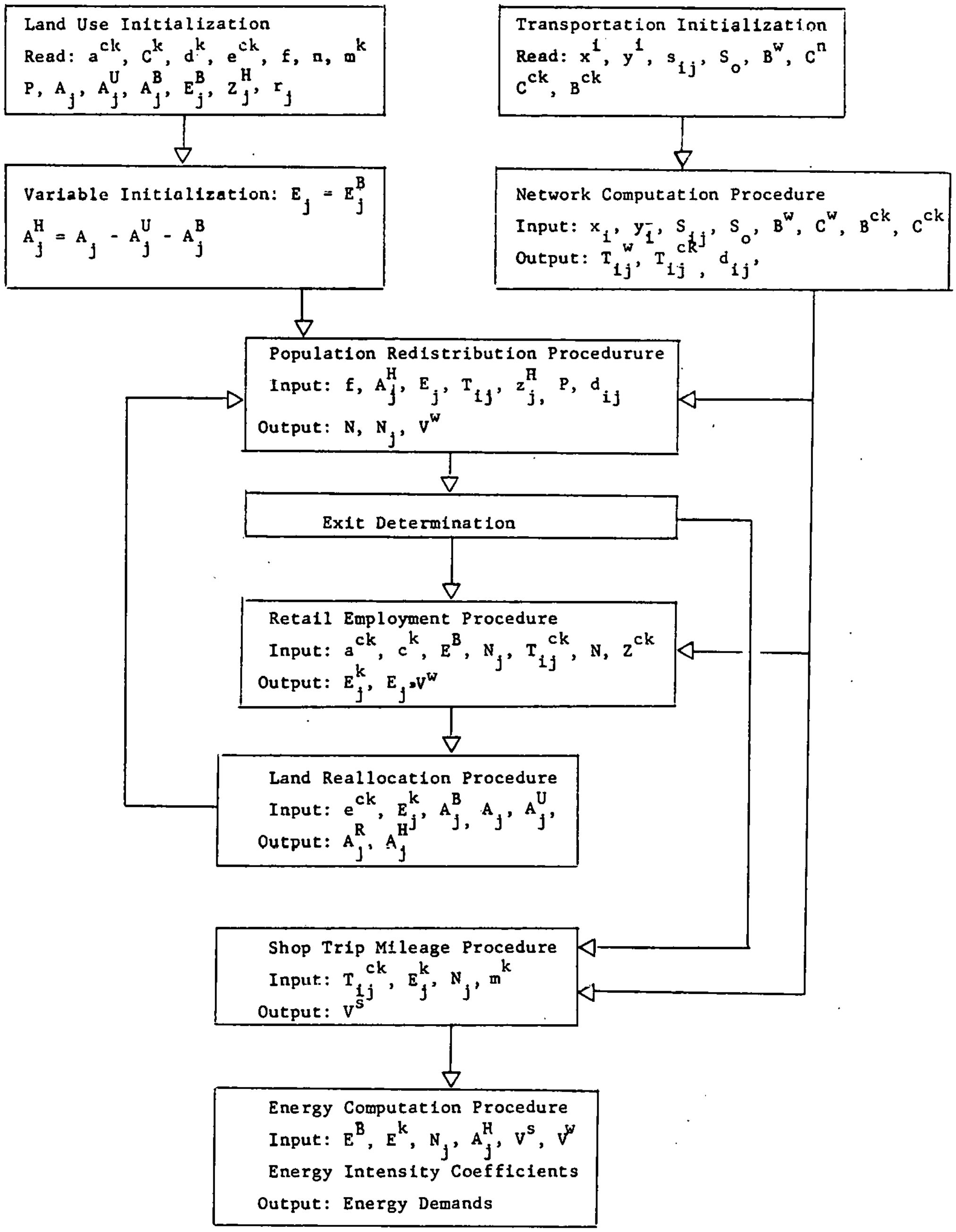
APPENDIX

COMPUTATIONAL FLOWS IN THE LAND USE-ENERGY SIMULATION MODEL

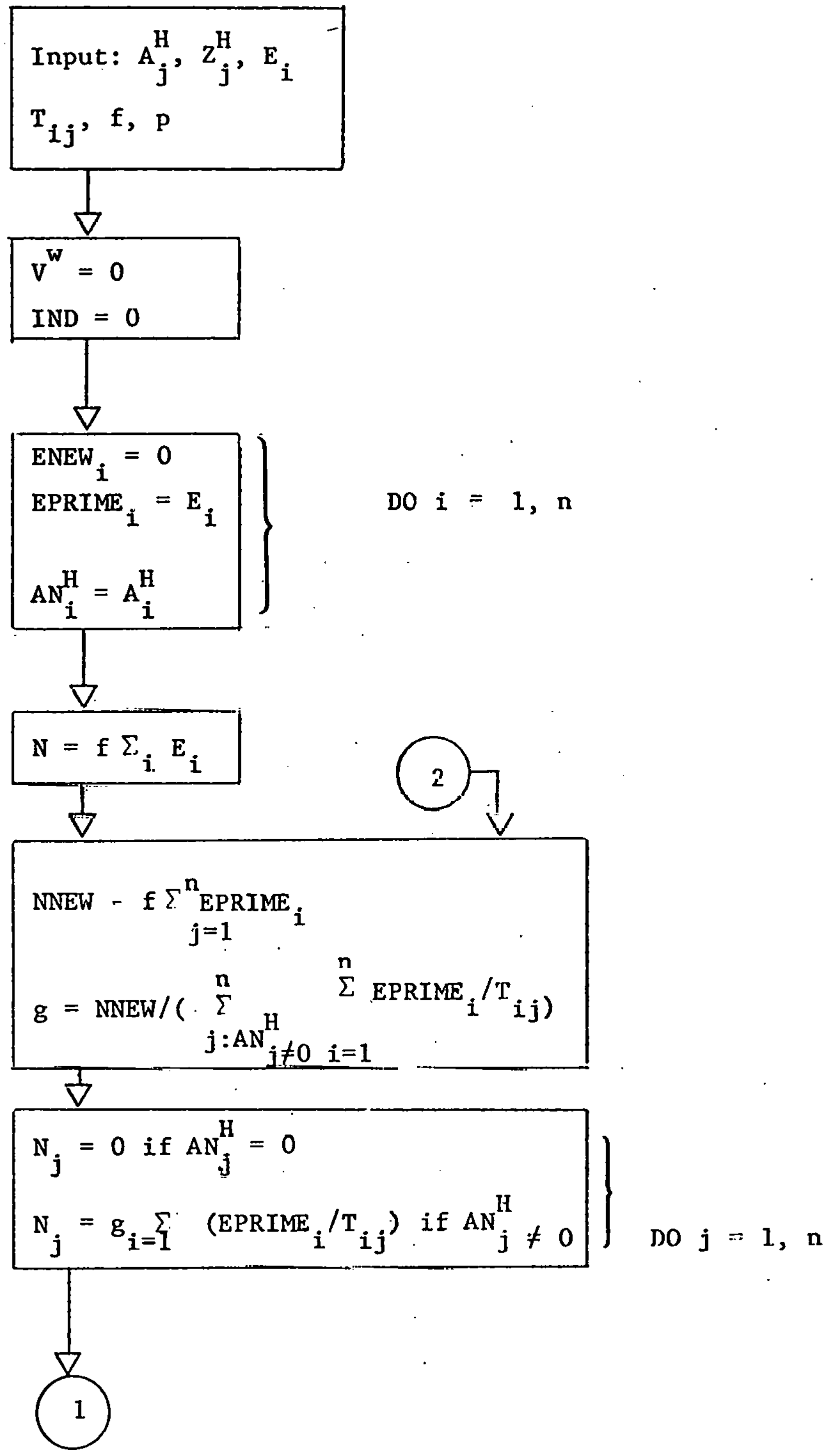
The following flowcharts illustrate the basic computational procedures of the model. The first flowchart describes the overall iterative scheme, and the following charts detail the procedures noted there. The variables correspond to those in the text, with the exception of some which are used for internal purposes only. Unfortunately, we are forced to use multi-letter variables (such as EPRIME) in some situations, having virtually exhausted the conventional alphabet.

We do not attempt here either to flowchart the entire FORTRAN program or even to detail all of the computational aspects of the model. Parts of the algorithm relating only to programming considerations are omitted entirely as are computations relating to higher levels of disaggregation. Including these aspects would necessarily complicate the description enormously while shedding little light on the procedure.

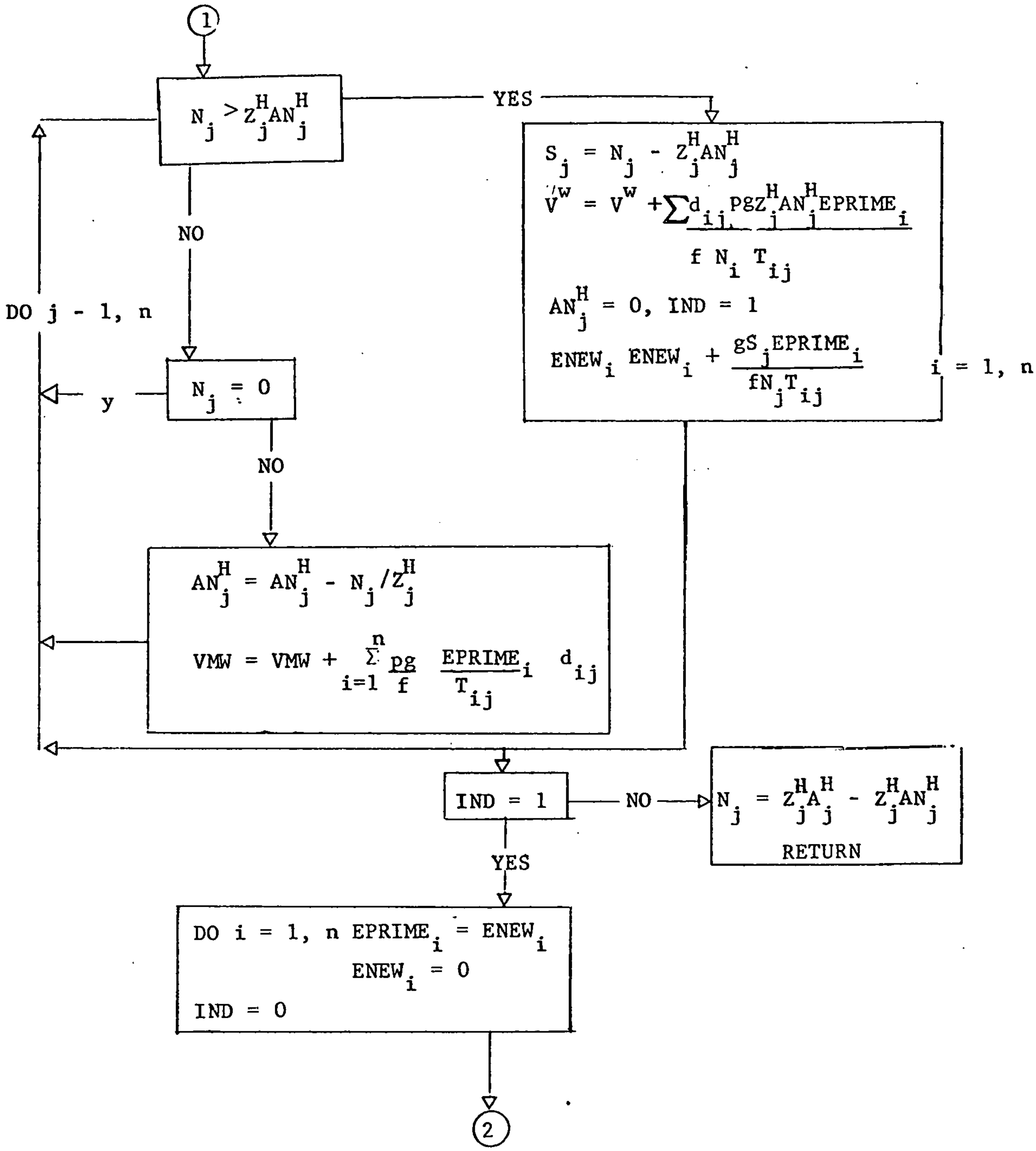
Appendix: Flow of Computational Procedures
Simulation Model



Population Redistribution Procedure (a)



Population Redistribution Procedure (b)



Network Computation Procedure

Input: $x_i$, $y_i$, $S_{ij}$, $S_o$
$B^w$, $C^w$, $C^{ck}$, $B^{ck}$

↓

$d_{ij} = ((x_i - x_j)^2 + (y_i - y_i)^2)^{1/2}$

$t_{ij} = s_{ij}^{-1}\ d_{ij}$, if i and j are accessible by highway

$S_o^{-1} d_{ij}$ if not

↓

Do for all i
Do for all j
Do for all k
if $t_{ik} + t_{kj} < t_{ij}$
Then $t_{ij} = t_{ik} + t_{kj}$
$d_{ij} = d_{ij} + d_{cj}$

↓

$T_{ij}^{ck} = (2\pi x\ (B^{ck} + C^{ck} x + x^2))^{-1}$

$T_{ij} = (2\pi x\ (B^w + C^w x + x^2))^{-1}$

## Shop Trip Mileage Procedure

Input: $T_{ij}^{ck}$, $N_j$, $E_j^k$

↓

$P_{ijk} = N_i / T_{ij}^{ck}$ For all i, j, 1, n: k = 1, m

$P'_{ijk} = 0$ IF $E_j^k = 0$

$P'_{ijk} = P_{ijk} \left( \sum_{j=1}^{n} P_{ijk} / \sum_{j:E_j^k \neq 0} P_{ijk} \right); \; E_j^k \neq 0$

i, j = 1, n

k = 1, 3

↓

$M^k = \sum_{i=1}^{n} \sum^{n} m_k P'_{ijk} d_{ij}.$ k = 1, m

$V^s = \sum_{k=1} M^k$

Energy Computation Procedure

Industrial Energy[+] $= \sum_{t=1}^{5} ENB_t \sum_{j=1}^{n} E_{j,t}^{B}$

Commercial Energy[+] $= \sum_{k=1}^{3} E^k \left( \frac{en_{ck}}{S_{ck} e^{ck}} \right)$

Transportation Energy[+] $= (V^w + V^s)\, t_e^{p,1}$

Housing Energy[+] =

For all j

Maximize $\sum_{m=1}^{5} c_m H_j^m$

Subject to $\sum_{m=1}^{5} H_j^m q^m < A_j^H$

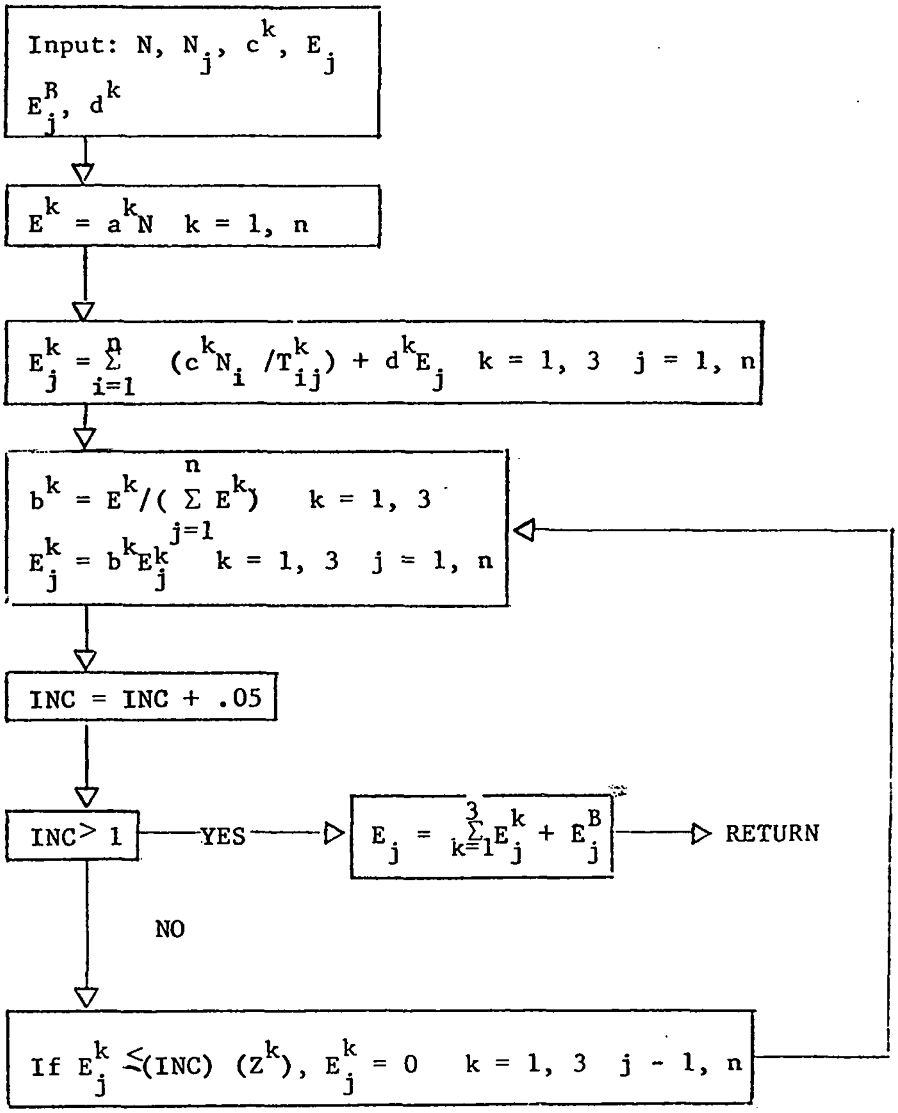
$\sum_{m=1}^{5} H_j^m = H_j$

$q^m H_j^m \leq fm\, A_j$

Housing Energy $= \sum_i \sum_m H_j^m G_m^1$

[+] For simplicity, all calculations shown here are at the least disaggregate level.

Retail Employment Procedure




Land Reallocation Procedure